Practical Overview of Mine Power System Harmonics

Western Mining Electrical Association

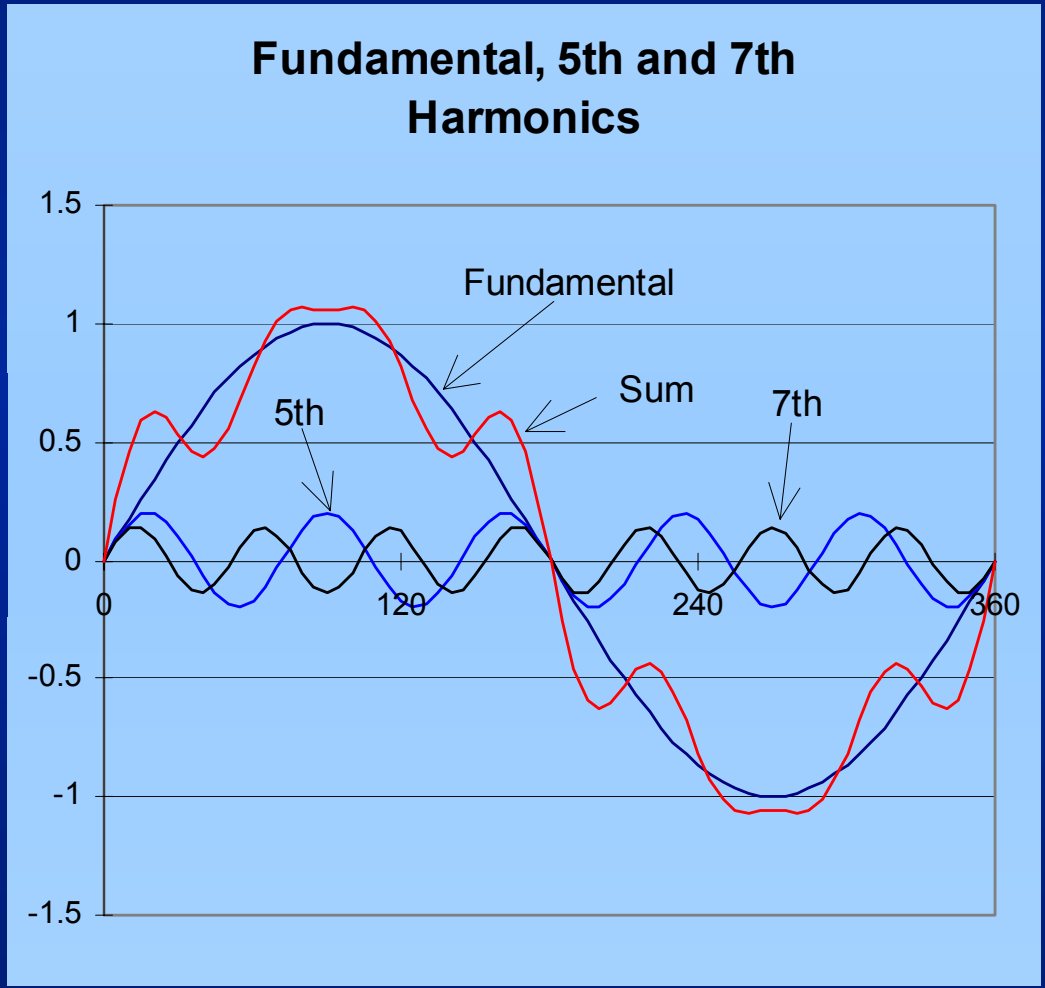
Tucson, Arizona
November 1999

Harmonic Topics

- What are harmonics?
- Where do they come from?
- Why worry?
- Standards.
- Solutions.

What Are Power Line Harmonics?

- "Harmonics" are voltages and currents at frequencies that are multiples of utility power frequency.



Where Do Harmonics Come From?

- Harmonic currents result from loads that draw power in non-sine-wave format.
- These are so-called non-linear loads.

Some Specific Harmonic Sources

Linear load examples:

- Resistance devices - heaters, incandescent lamps
- Induction motors
- Capacitor banks

Non-Linear load examples:

- Transformers during energization
- Arc welders and arc furnaces
- Ballasts.
- Rectifiers
- Computers, switching power supplies
- DC drives, AC Drives
- Switched cap banks

Some Harmonic Producers

Harmonic Producer	Harmonic	Notes
Transformers during energization	2nd	Gone after 0.1 sec
Arc Welders and Furnaces	Broad spectrum, 2nd, 3rd, 4th, 5th, 7th, 11th	Filters usually included
Ballasts, electronic	3rd, 5th, 7th	3rd cancelled in delta transf
Plating Rectifiers	Typical 5th, 7th, 11th, 13th, etc, magnitude 1/n	Varies by number of pulses
Computers, switching power supplies	3rd, 5th, 7th	3rd cancelled in delta transf
DC Drives	Typical 5th, 7th, 11th, 13th, etc, magnitude 1/n	Varies by number of pulses
AC drives	Typical 5th, 7th, 11th, 13th, etc,	Varies by type, number of pulses, system Z
Switching Cap banks	High frequencies, depend on system	Transients, induce system resonances

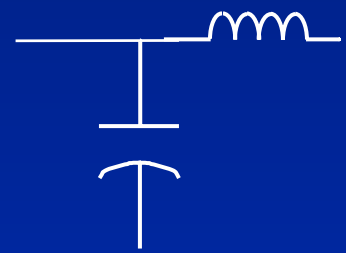
Why Worry?

OR - What makes Power system Harmonics so bad?

- Capacitors can blow from overvoltage
- Drives can trip offline
- Transformers can overheat - possibly to destruction
- Motors will heat more
- Ballasts can pop
- Electronics can malfunction

A Closer Look: Capacitor Loss from Harmonic Overvoltages

- Every AC distribution system has distributed inductance L & capacitance C.
- Adding pf correction caps anywhere in the system will produce a resonant point with system L



$$\text{Harmonic Number of Resonance} = \sqrt{\frac{\text{Short Circuit MVA}}{\text{Capacitor MVAR}}}$$

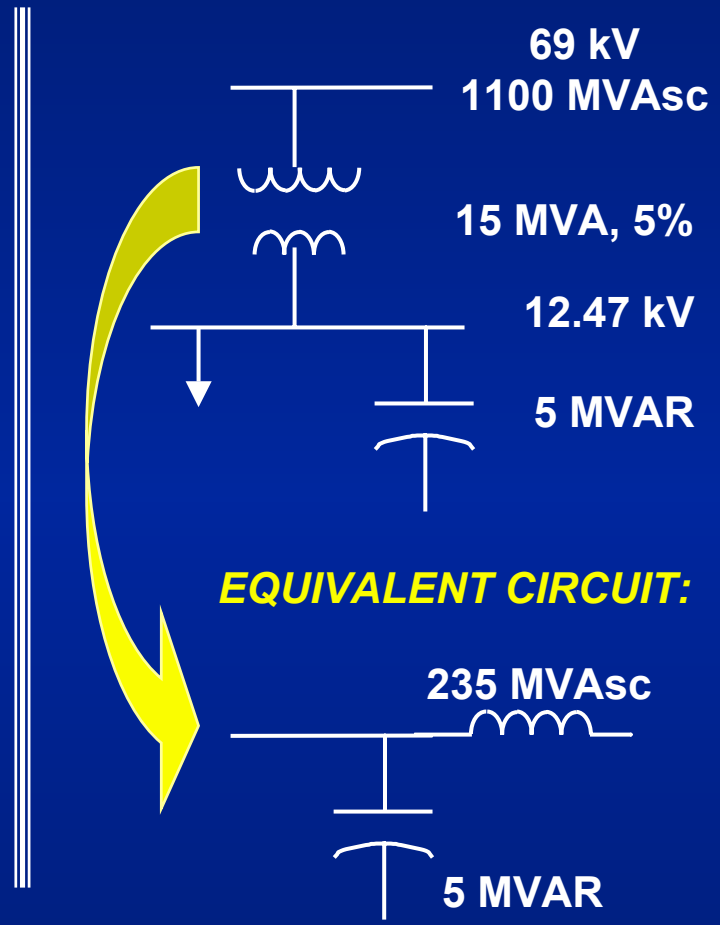
IF THIS "HAPPENS" TO CORRESPOND TO A HARMONIC CURRENT PRESENT IN THE SYSTEM, THE RESONANCE WILL PRODUCE BIG VOLTAGES ON THE CAP BANK!

Example: PF Cap Bank in Harmonic Trouble

System KV = **12.47**
Equiv. System MVAsc = **235**
Capacitor Bank Mvar = **5.0**

$$\text{Harmonic Number of Resonance} = \sqrt{\frac{\text{Short Circuit MVA}}{\text{Capacitor MVAR}}}$$

Approx Harmonic Resonance = 6.86 !



CAP BANK AND SYSTEM Z RESONATE NEAR 7th HARMONIC!
ANY DRIVE OR RECTIFIERS ON THE SYSTEM COULD CAUSE HUGE OVERVOLTAGES!

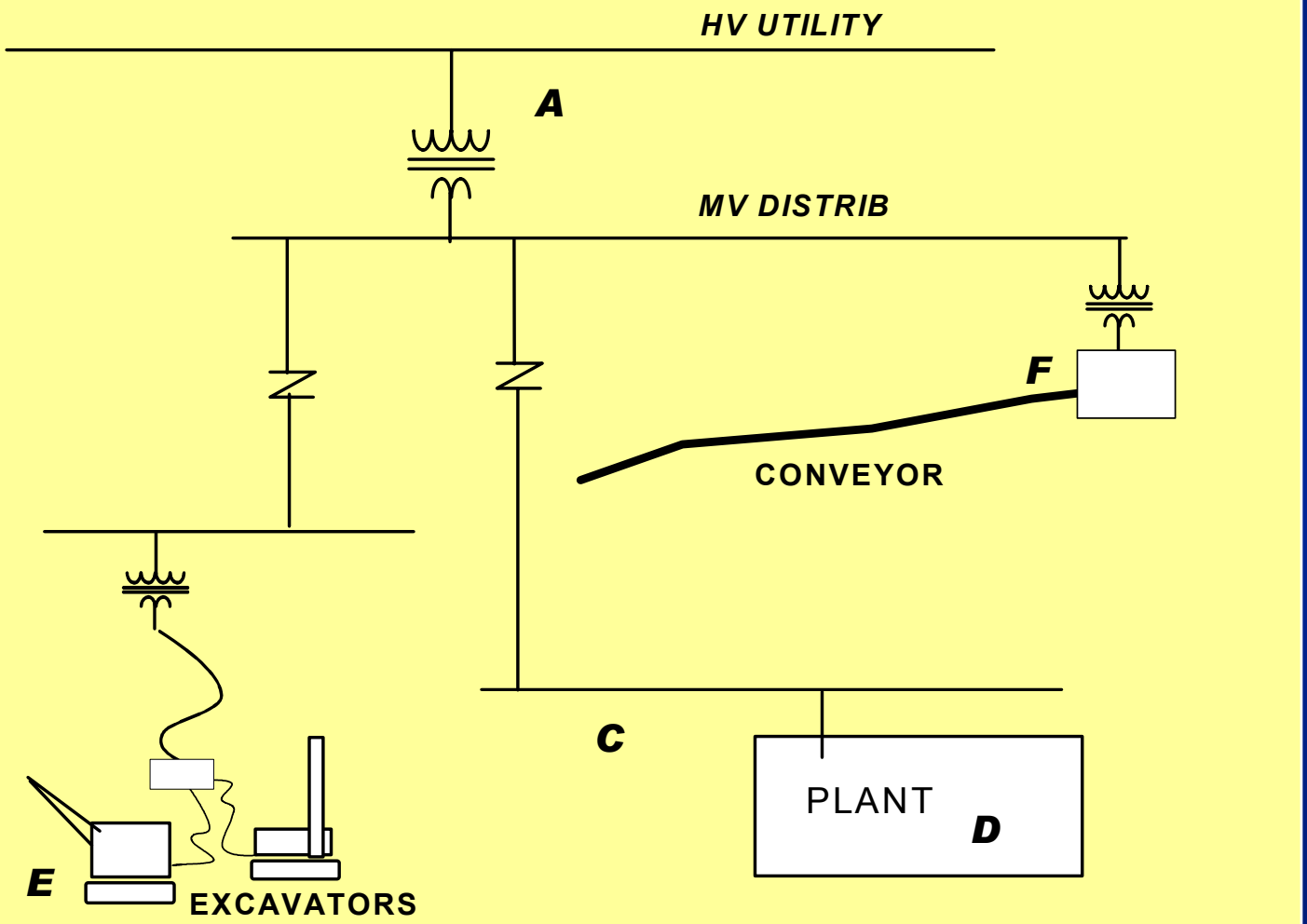
Symptoms of Capacitor Series Resonance

- Voltages across caps measure higher than 10% over nameplate rating, scope shows high peaks.
  - ❖Be sure to use True-RMS meter
  - ❖Over-voltages can come and go with operation of harmonic producing equipment.
- Capacitor “Cans” are swollen
- Cap Fuses blow, cans fail

Fixing System Resonance Problems

- Experiment or calculate to verify problem
  - ❖Calculate using simplified approach
  - ❖Temporarily remove caps and observe effect.
- Remove proven offending cap banks
- OR, Change size of bank
- OR, Tune the bank with inductors

Example Power System



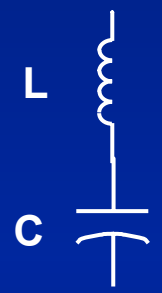
The P.F. Correction Dilemma

A. Harmonic producers such as drives often need power factor correction.

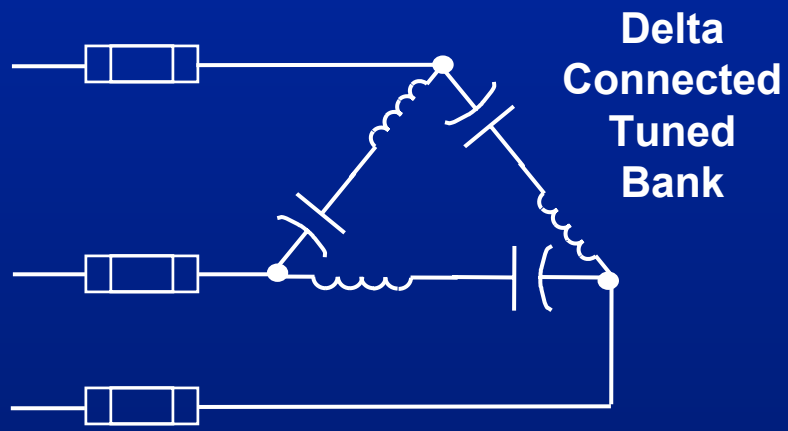
B. Naked capacitors will likely resonate and cause problems

Tuned Capacitor Banks
[Also Known As Harmonic Filters]

- Naked capacitors often cause resonance problems on system
- Inductors and capacitors in series combinations at resonant frequency look like near zero ohms.
- If tuned to harmonic frequency, LC filter will act as sink for that frequency

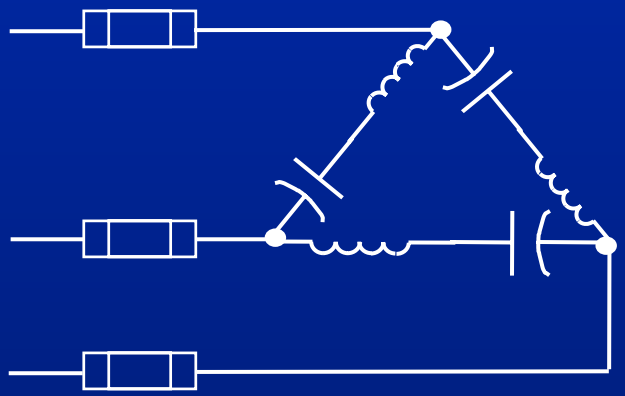


$$\text{Res Freq} = \frac{1}{2\pi(LC)^{.5}}$$

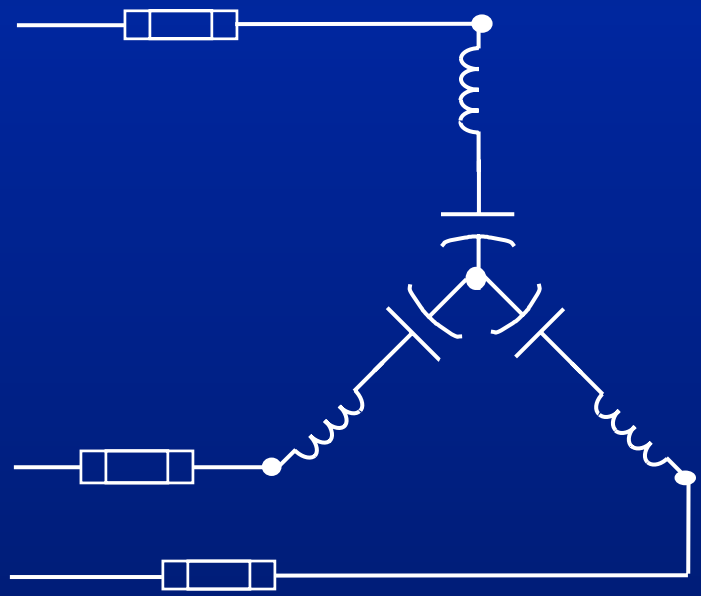


Tuned Capacitor Banks
Configurations

Delta Connected Tuned Bank - frequently used in LV filters.



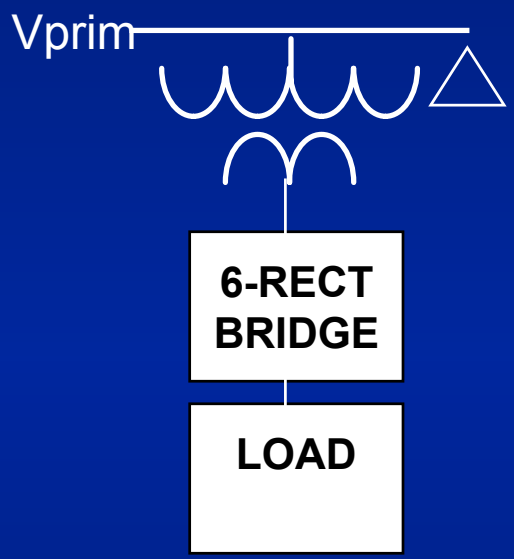
Wye Connected Tuned Bank - frequently used in MV filters.



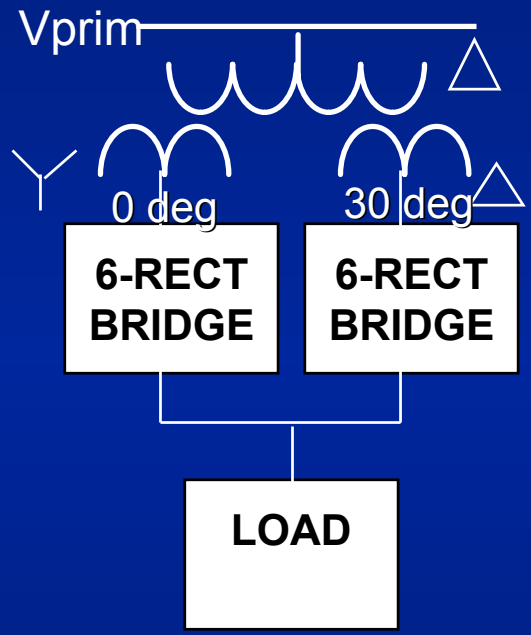
Harmonic Filters

- Medium voltage or low voltage
- Tune to below desired trap frequency [example, 4.7th]
- Rising temps move up resonance
- Filter LC is in parallel with system z - causing ANOTHER resonant point
- New parallel resonant point is hopefully not on critical frequencies

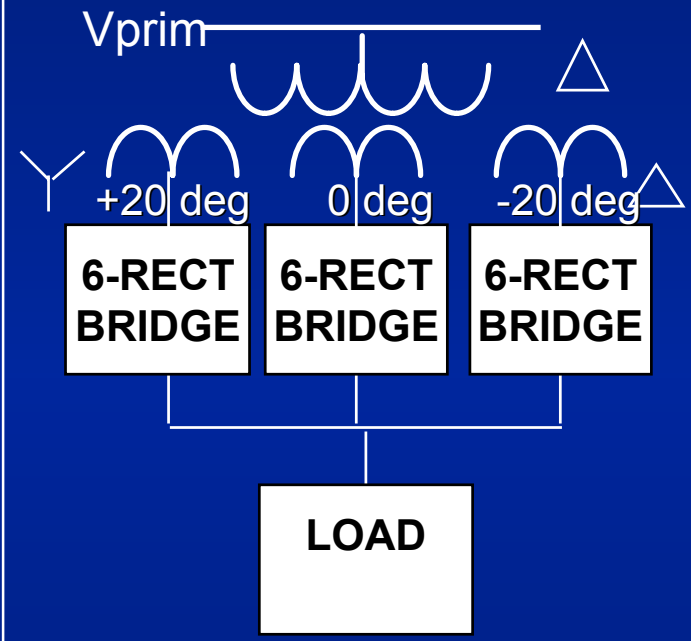
Multipulse Rectifier Circuit Comparison



6-PULSE RECTIFIER
5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th Etc.



12-PULSE RECTIFIER
5th, 7th 90% cancelled still have 11th, 13th, 17th, 19th, 23rd, 25th Etc.



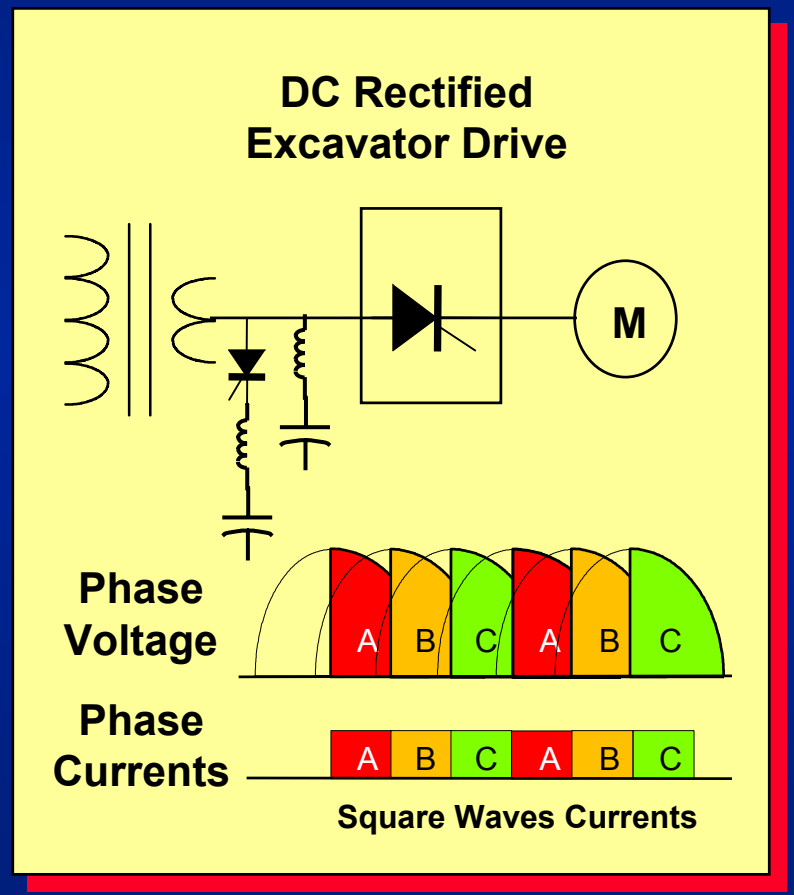
18-PULSE RECTIFIER
5th, 7th 11th, 13th 90% cancelled still have 17th, 19th 23rd, 25th Etc.

Plating Rectifiers

- Power range 1-10 MVA
- Thyristor [SCR] phase controlled
- Frequently 12 pulse configuration to cancel 5th and 7th harmonics
- Filters are on transformer primary side.
- Small 5th and 7th plus 11th and 13th filters.

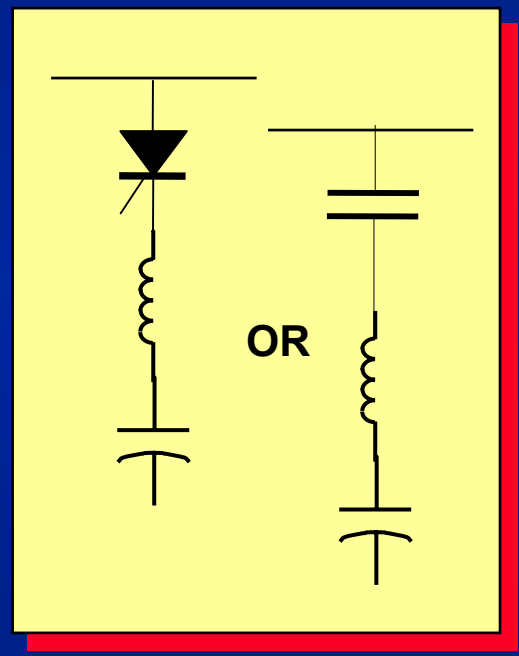
DC Drives

- Phase controlled SCR drives, phase amps in square wave blocks
- Usually have PF comp and Filters onboard.
- Typical 5th, 7th etc at 1/N magnitude.
- HF ringing harmonics due to switching.
- Switched caps on P&H individually tuned.
- LAG PF at stall very poor w/o caps.

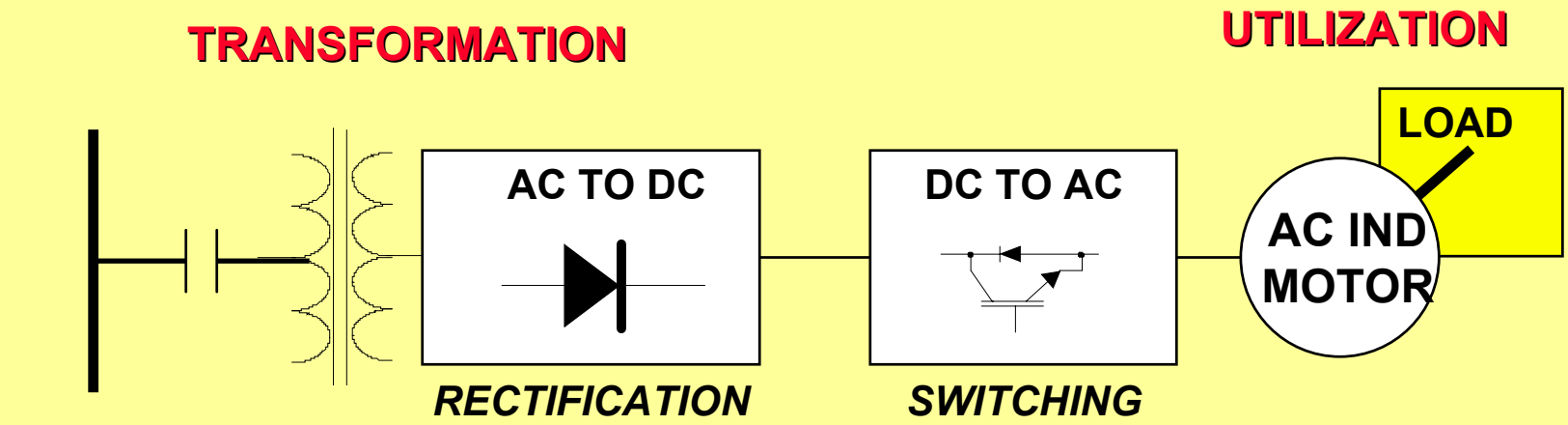


Switched Capacitor Banks

- Contactors or SCR's can be used.
- Provide automatic compensation of variable PF demands
- Switched banks must be individually tuned.
- Can introduce HF ringing harmonics due to switching.

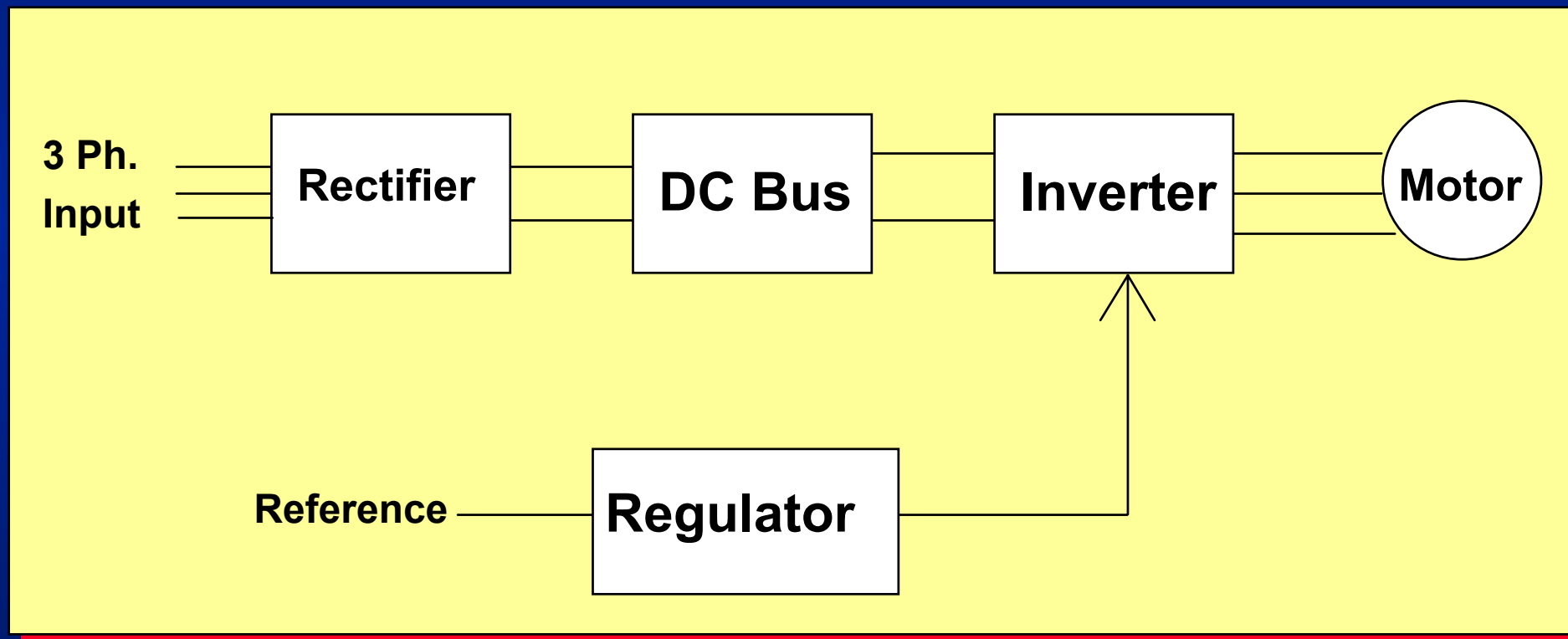


Power Conversion
AC Inverter

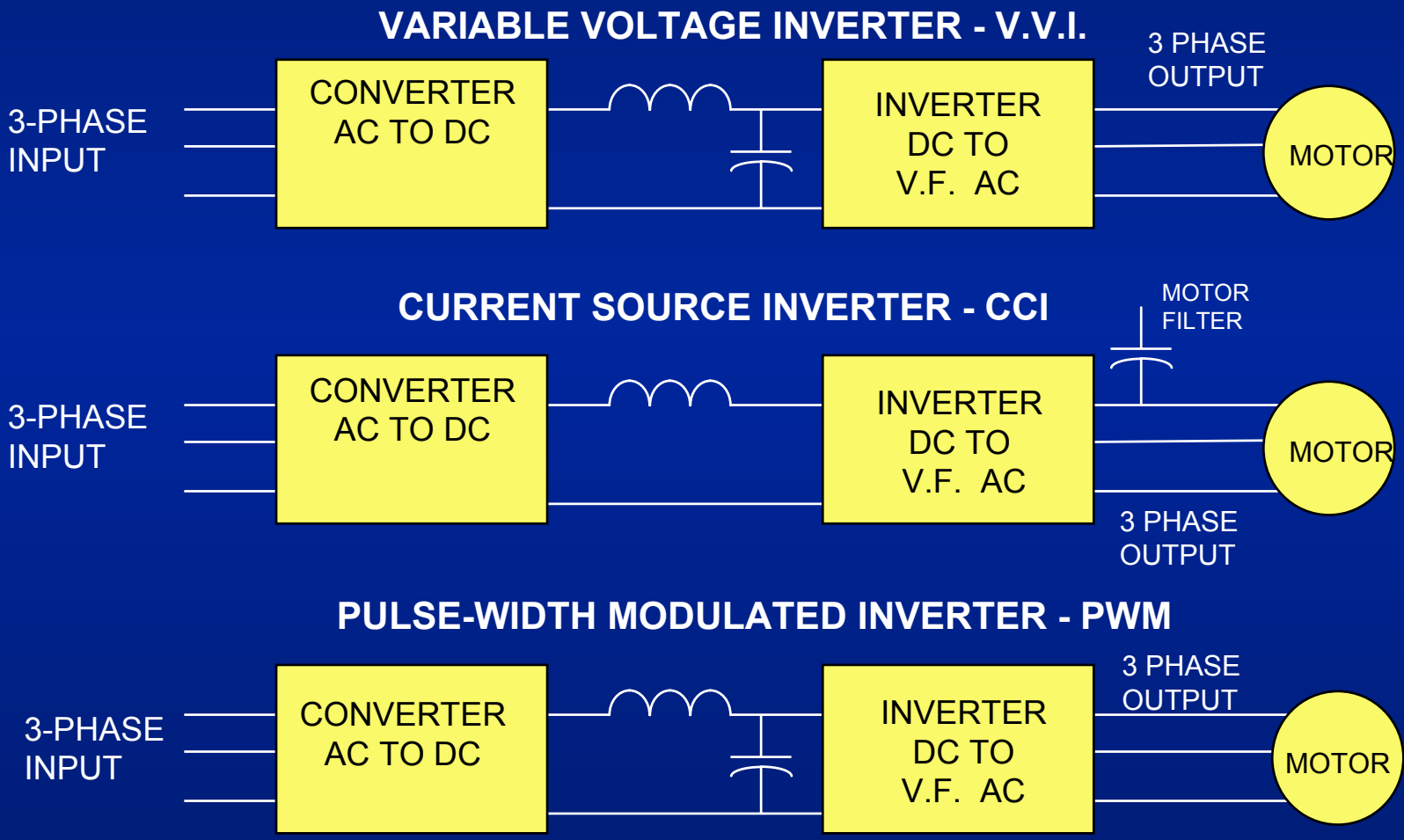


AC INVERTER TECHNOLOGY
UP TO 97% EFFIC

Inverter System
General Block Diagram



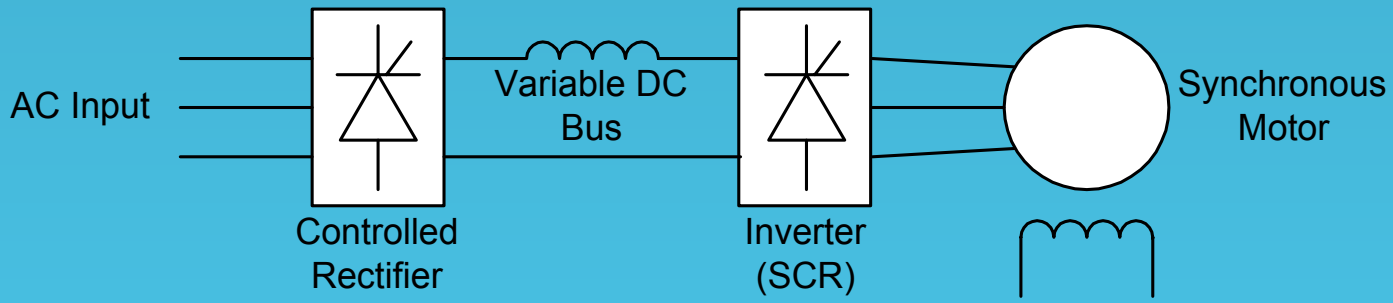
BASIC AC DRIVE TYPES



AC-VFD Current Source Drives

- All have phase-controlled front ends.
- DC Link inductors keep current continuous
- Inverter switches curent to the motor phases.
- Used for large induction or sync motors
- Looks like a DC drive to the power line, with similar harmonics.

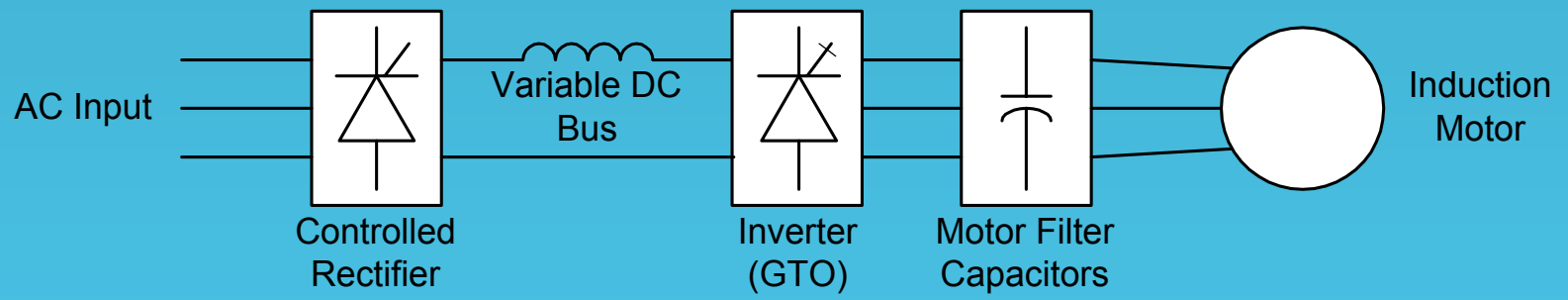
Load Commutated Inverter



Inverter Bridge Topology Comparison

Inverter Topology	Advantages	Drawbacks	Practical Power Range
Load-commutated Current source SCR Inverter	• Low Parts Count • Full Regen and DB possible • Rugged • Economical High HP	• Requires a controlled front end • High motor current THD • Slow transient response • Narrow motor frequency range • Minimum Starting Torque • Poor low speed performance • Synchronous Motor	Above 2 MW

Current Source PWM GTO Inverter

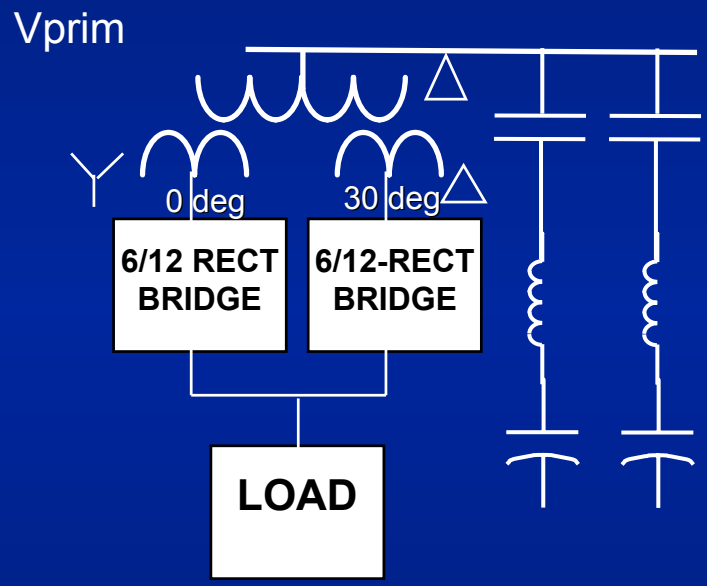


Inverter Bridge Topology Comparison

Inverter Topology	Advantages	Drawbacks	Practical Power Range
Current Source GTO PWM Inverter	• Full regen and DB possible • Low parts count • Low motor THD • Low motor insulation stress	• Requires a controlled front end • Poor input power factor • Low switching frequency • Slow transient response • Narrow motor frequency range • Poor multi-motor operation	2 - 15 MW

Typical Large CSI Drive
PF Correction & Harmonic Filters

- Often 12 pulse AC front end is used to reduce 5th and 7th harmonic currents
- Poor PF at low speeds requires caps to correct
- Banks must be tuned.
- Small 5th & 7th still needed, plus 11th.



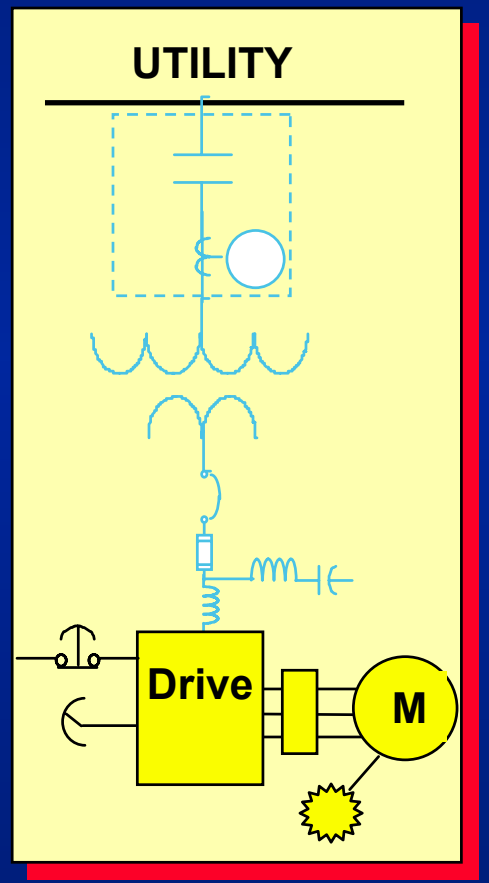
12-PULSE RECTIFIER
5th, 7th 90% cancelled
still have 11th, 13th,
17th, 19th, 23rd, 25th Etc.

AC PWM Drives

- The most frequent AC drives in use today.
- LV or MV drives - usually use diode front ends.
- Create unique PF and harmonic problems.

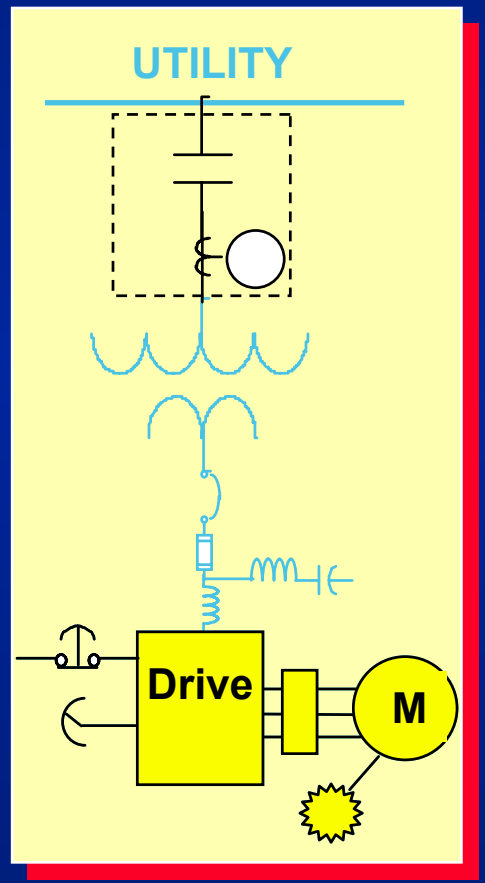
Utility Considerations

- Stiffness of supply
- Utility power level variations
- "Quality" of power as received
- Restrictions on power quality effects by new installation [power factor, harmonics]
- Impact of new loads on existing system.



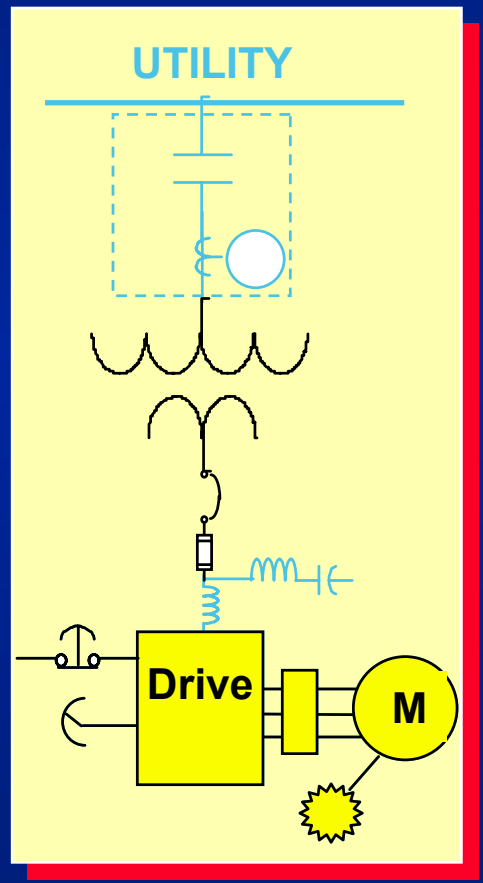
Power Control and Protection

- Medium Voltage switchgear
- Unique needs of drive-dominated loads.
- Metering, monitoring, and power management.



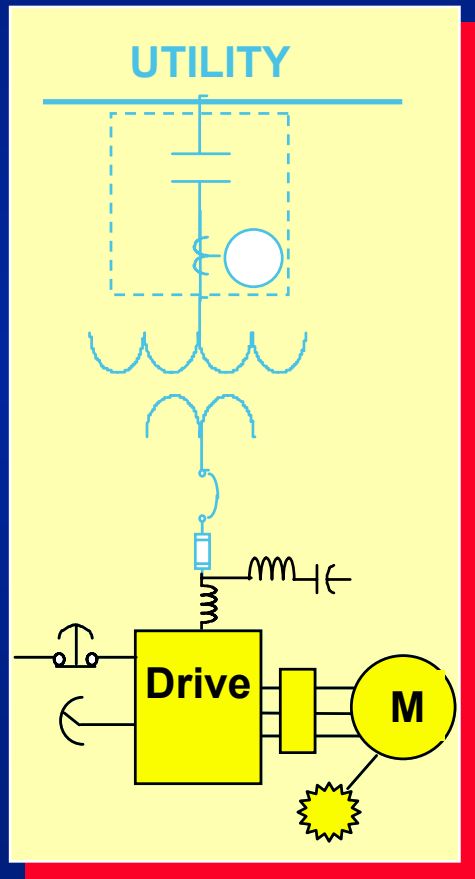
Power Distribution

- Harmonic effects on equipment
- True meaning of power factor
- Feeder sizing
- Mixture of drive and non drive loading.
- Transformer rating factors

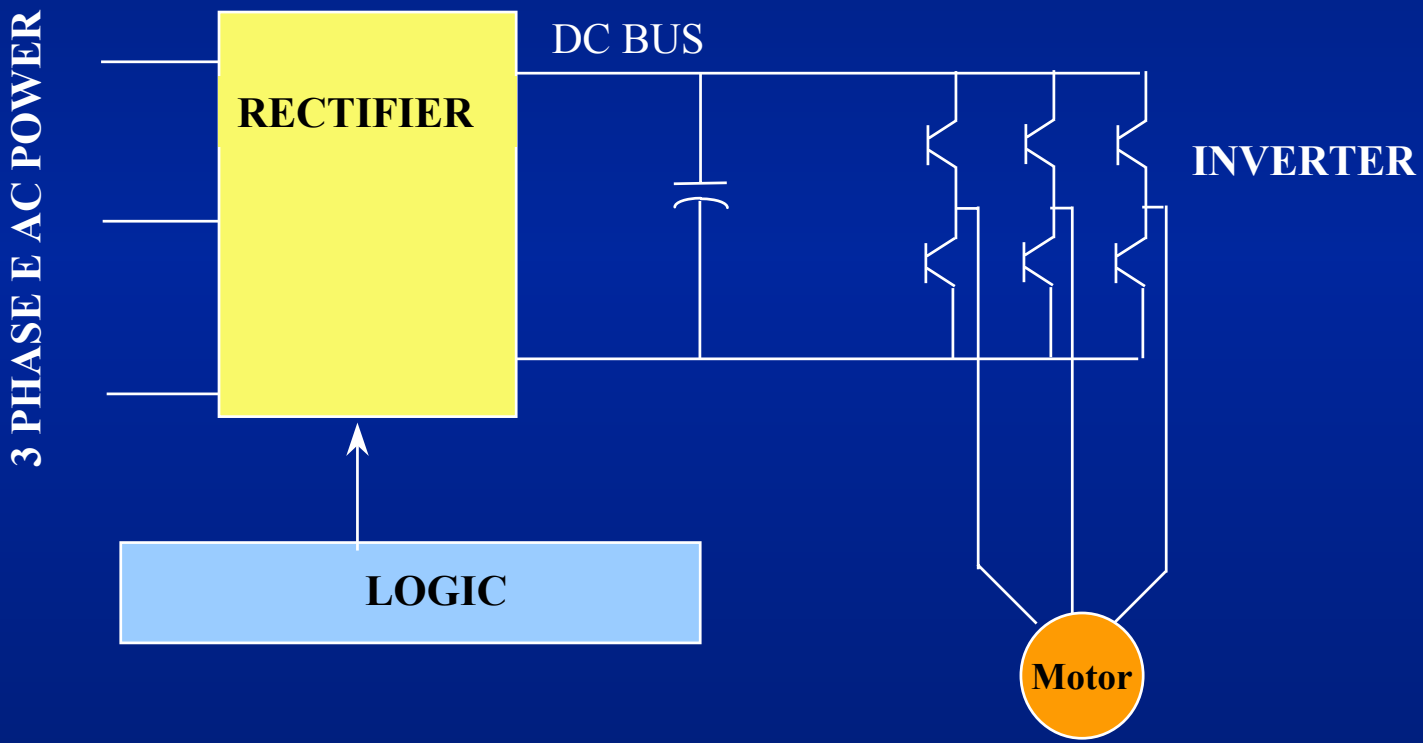


Power Quality Issues

- Power disturbances on existing system.
- Injection of harmonics -
  - The problem & true impact
  - Specs, recommendations & regulations [IEEE-519 & others]
  - Rational solutions
- Economic tradeoffs.



PWM AC Drive Block Diagram



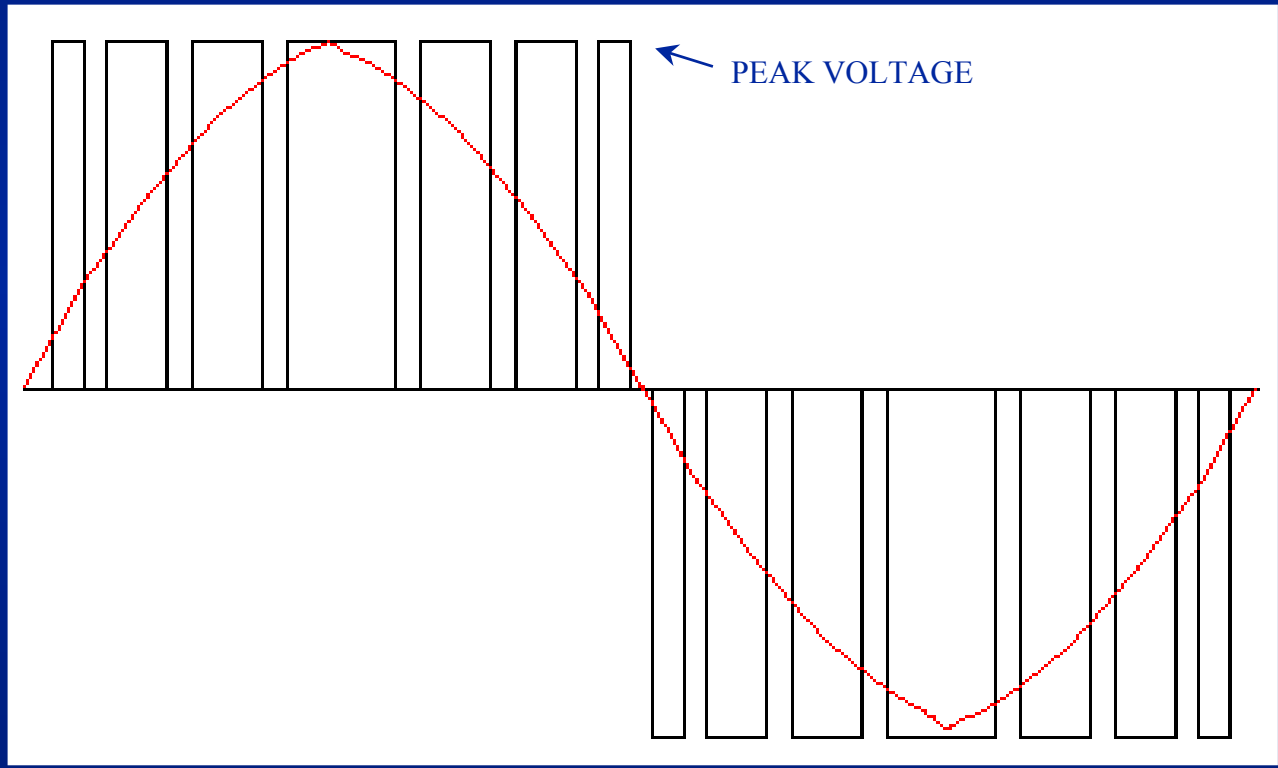
Pulse-Width-Modulated [PWM] Wave Form

Voltage = The Average of the time the Voltage is on Plus the time the Voltage is Off.

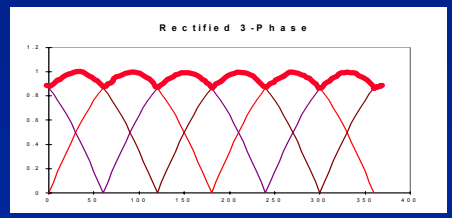
The Motor tends to smooth the voltage wave

Present designs use IGBT devices to produce smooth current waves.

IGBT devices switch at rates up to 20K Hz.



Low voltage PWM drive



3 Phase
Diode Bridge

[+]

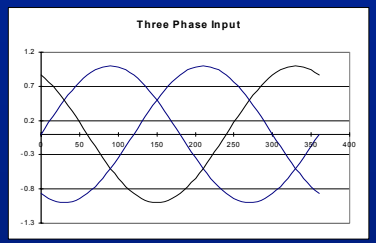
DC Buss Rectified Power

AC Incoming Line

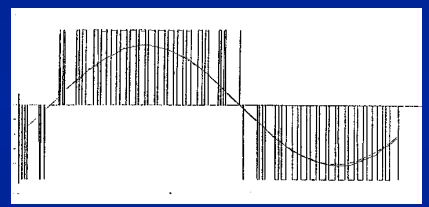
Cap Bank

DBR

[-]

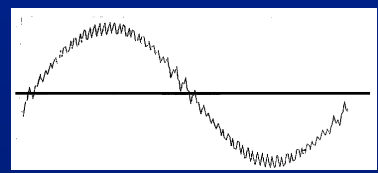


PWM Motor Volts



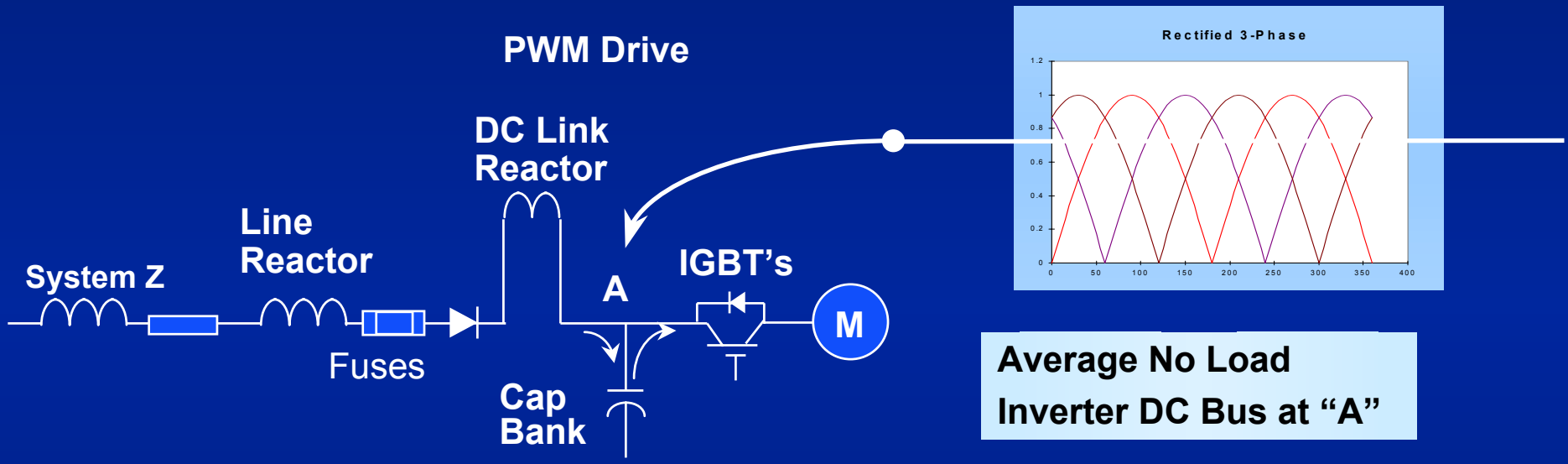
a
b
c

M



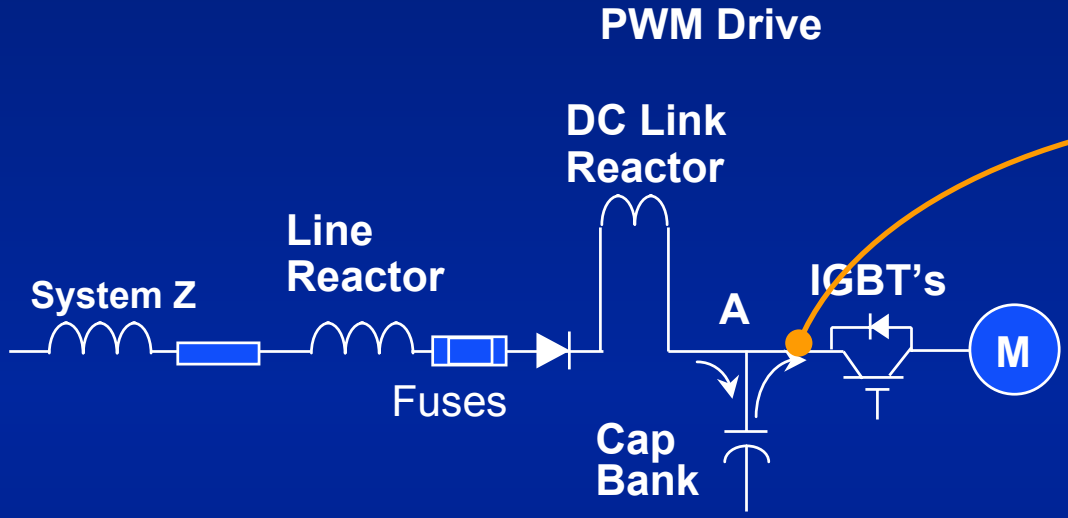
Motor Amps

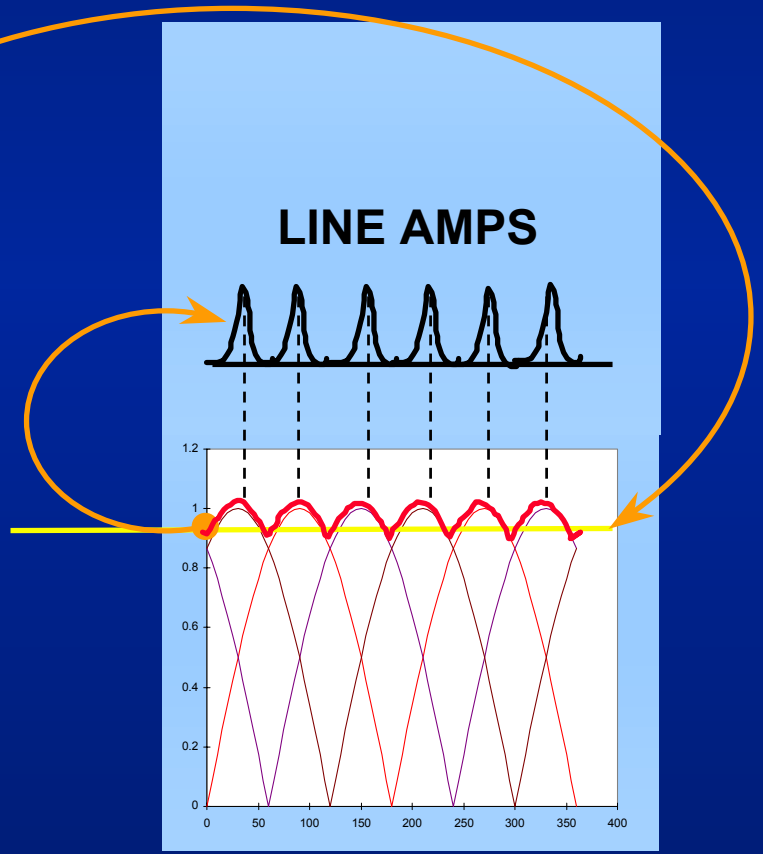
Inverter System Power Components



- General Rule: 5% Z needed in System Z + Line Reactor OR include DC Link reactor to Prevent Fuse Blowing.
- Some drives have SCR in rectifier to control charging.
- Line reactor &/or DC reactor Improve average power factor & reduce Harmonics

Inverter System AC Line Distortion





CAPACITOR CAN FILL ONLY WHEN PEAK LINE VOLTS AT A ARE ABOVE CAPACITOR VOLTS:

*** LINE AMPS CHARGE CAPS IN VERY UNEVEN BUMPS [NOT SINE WAVE!]**

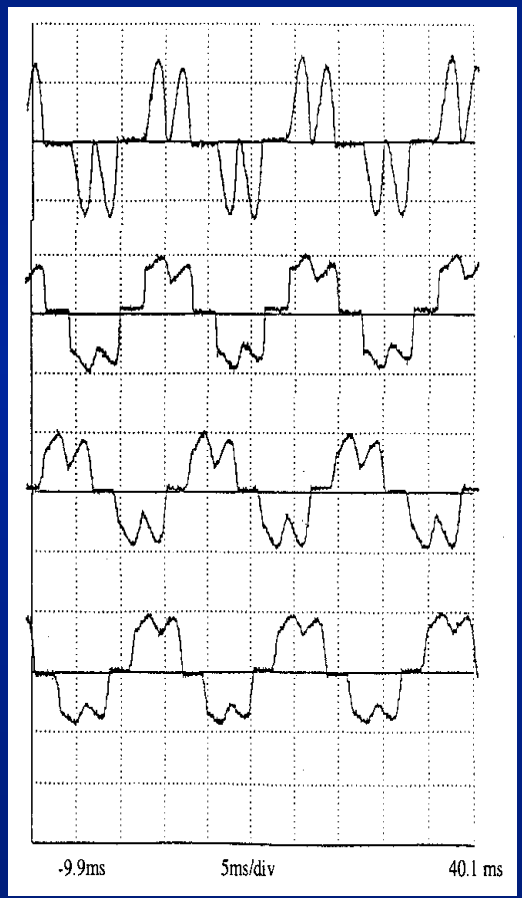
*** NON SINE WAVE CURRENT IS FULL OF HARMONICS.**

Displacement vs Real Power Factor

- Drives are usually specified in "displacement power factor", DPF
- DPF = cosine of phase angle between supply volts and line amps.
- For diode front end PWM, DPF > .95
- True PF = KW / KVA
- True PF can be quite bad. PF =0.60 not uncommon! Depends on Line Z.

Effects Line & DC Reactors on Power Line

AC Line Amps



Base line

DC Link Reactor

AC Line Reactors

DC Link & & AC line Reactors

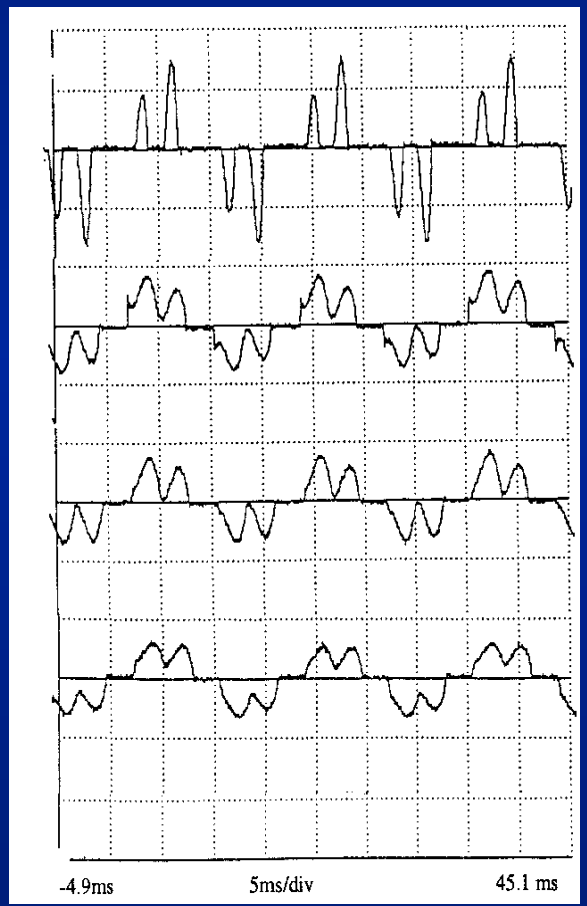
Soft Source 30 KVA, 5.5% Zt

	Baseline	DC Link Reactor	AC Line Reactors	Ac and DC Reactors
Input KVA	**5.9**	**5.0**	**5.0**	**5.0**
Avg Inp Volts	469	467	471	468
Avg Ph Amps	**7.2**	**6.2**	**6.1**	**6.2**
Input VoltageThd..	5.0%	3.2%	2.8%	2.6%
Input Current Thd	**69.1%**	**31.8%**	**34.2%**	**27.8%**
Input Volts Imb	0.1%	0.1%	0.1%	0.2%
Input Amps Imb	4.8%	2.4%	5.5%	0.8%
Input True PF	**0.81**	**0.94**	**0.91**	**0.93**
Mot Amps THD	3.5%	3.0%	3.0%	3.3%

Ref Page 12-9 & 12-10 GEZ-7984E

Effects Of Line & DC Reactors on Power Line

AC Line Amps



Base line

DC Link Reactor

AC Line Reactors

DC Link & & AC line Reactors

Stiff Source 180 KVA, 2% Zt

	Baseline	DC Link Reactor	AC Line Reactors	Ac and DC Reactors
Input KVA	**5.2**	**3.8**	**3.2**	**3**
Avg Inp Volts	469	467	470	469
Avg Ph Amps	**6.2**	**4.7**	**4**	**3.7**
Input VoltageThd..	1.70%	1.40%	1.20%	1.30%
Input Current Thd	**129.0%**	**54.7%**	**58.3%**	**39.4%**
Input Volts Imb	0.30%	0.30%	0.40%	0.30%
Input Amps Imb	13.9%	11.6%	6.8%	4.8%
Input True PF	**0.61**	**0.85**	**0.83**	**0.9**
Mot Amps THD	4.2%	3.3%	4.4%	4.1%

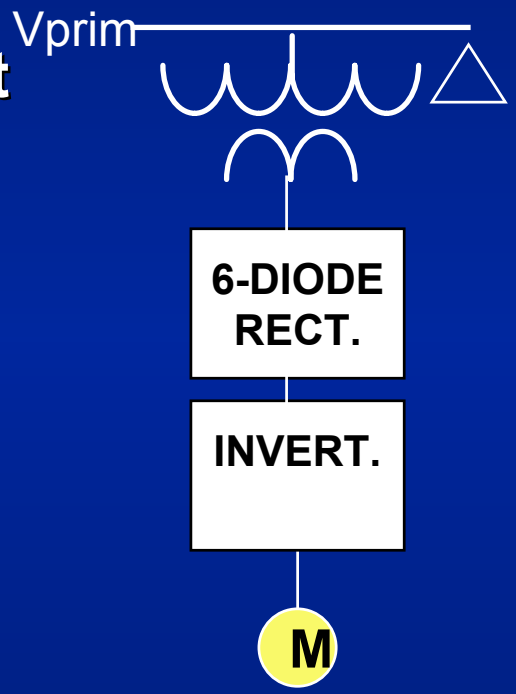
Ref Page 12-9 & 12-10 GEZ-7984E

Power System Compatibility-Supply

- Fast-acting current limiting AC line fuses protect input rectifiers and limit fault current.
- Added reactance in AC line or DC link is needed when feeder transformer kVA is >10 times drive HP to prevent fuse blowing.
- System reactance [native or added] GREATLY reduces line KVA and harmonic currents

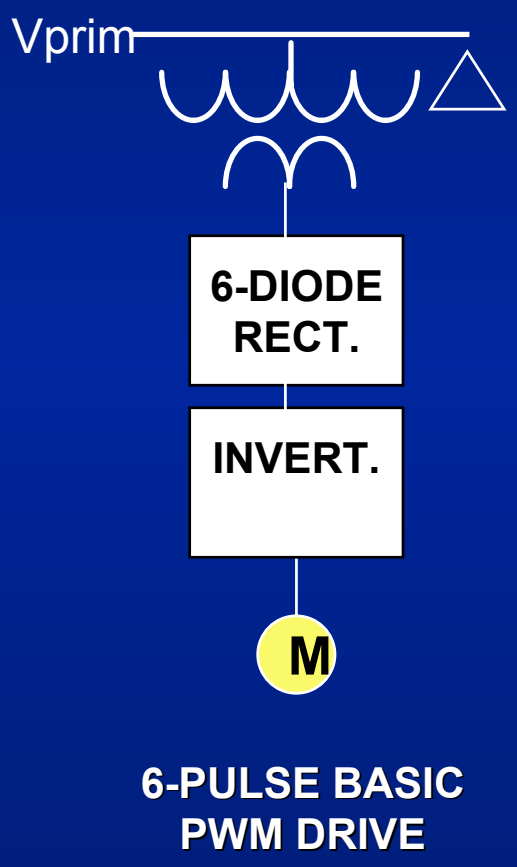
Drives "Pulse" Number Overview

- Simple full-wave drive rectifier front end has 6 diodes
- Each diode gives a pulse of output voltage for every peak of 3-phase voltage.
- Higher "pulse" drives use more diodes in rectifier section.
- Each rectifier fed from own transformer secondary

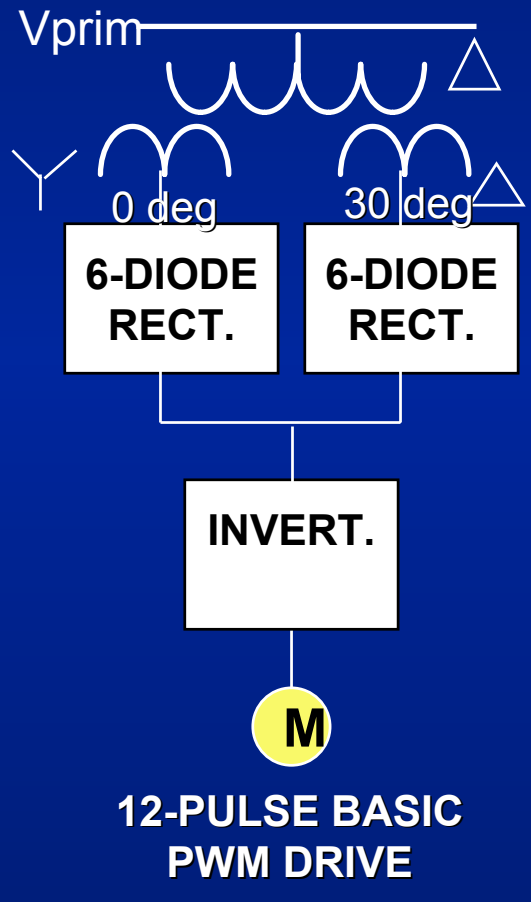


6-PULSE BASIC PWM DRIVE

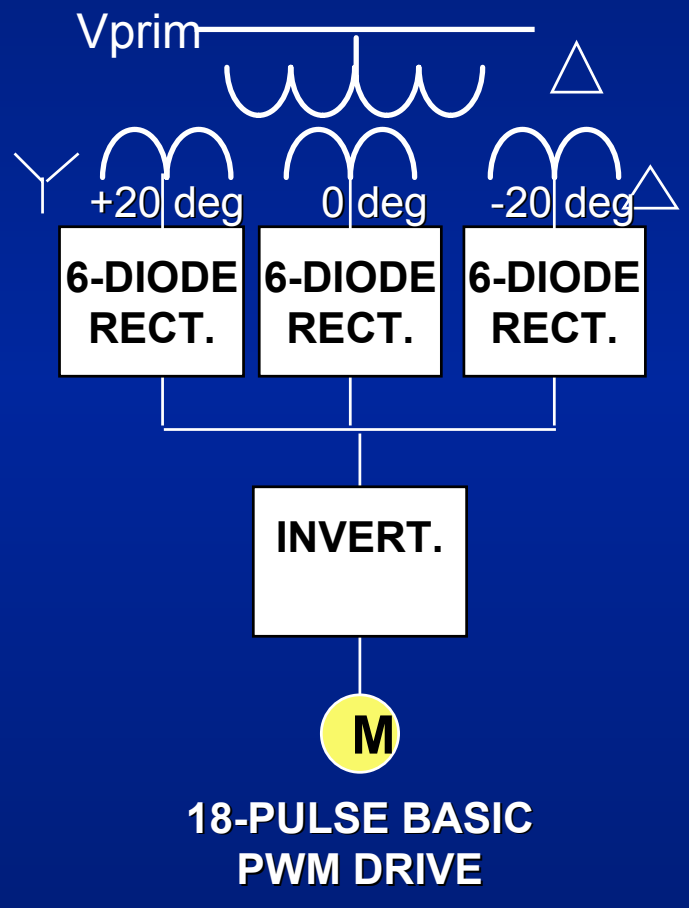
Multipulse Drives Circuit Comparison



6-PULSE BASIC PWM DRIVE

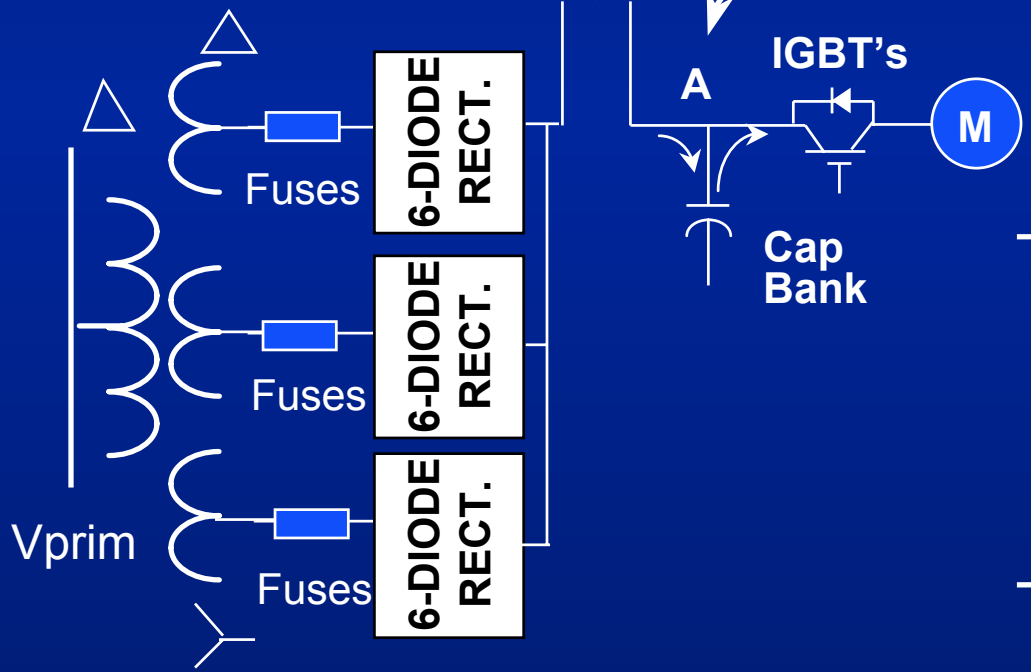


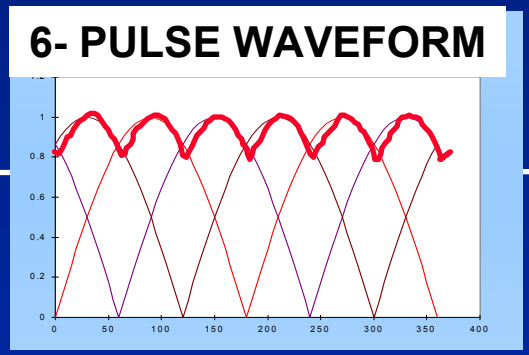
12-PULSE BASIC PWM DRIVE

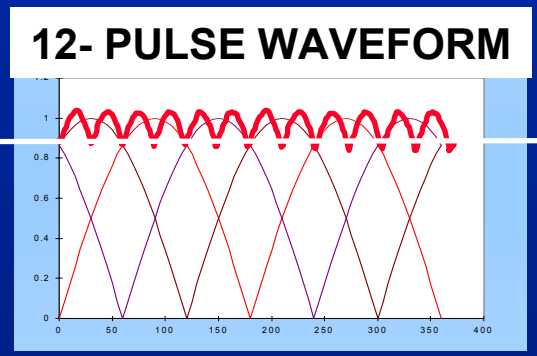


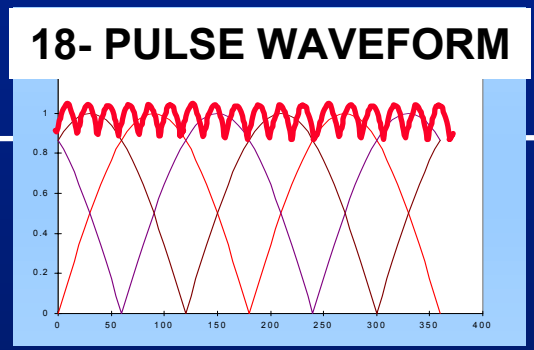
18-PULSE BASIC PWM DRIVE

Multi-pulse LV PWM Drives





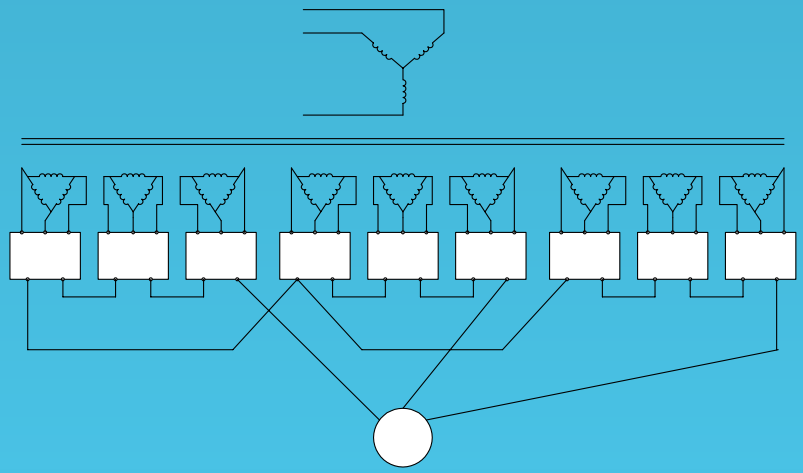


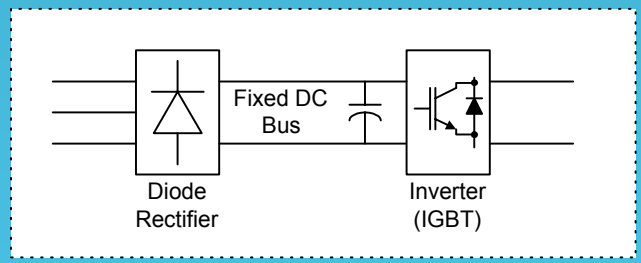


"Pulse Count" Drive Comparison

Factors → / Cost ↓	6 Pulse	12 Pulse	18 Pulse
Cost	Lowest	More	Most
Transformer	None, or Simple [Can Share]	Special, Dedicated	Special, Dedicated
Harmonics [drive only]	Large TDD	11-17 % TDD, 90% of 5th & 7th cancel	<5 % TDD, 90% of 5th to 13th cancel
Complexity / Parts Count	Simplest	More	Most
Potential Reliability	Most	Less	Least

Multi-level Voltage Source IGBT PWM Inverter

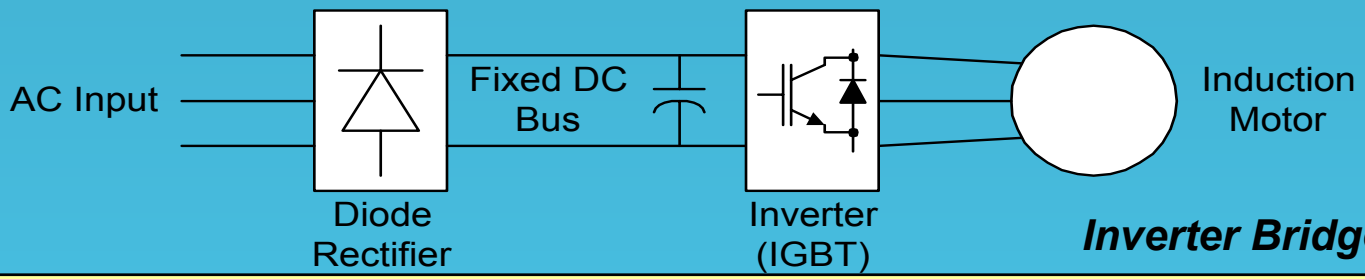




Inverter Bridge Topology Comparison

Inverter Topology	Advantages	Drawbacks	Practical Power Range
Multi-level Voltage Source IGBT PWM Inverter	• Low motor current THD • Low motor insulation stress • Partial N+1 redundancy available • Easy repair • Fast transient response • Wide motor frequency range • High power factor •Low power system harmonics	• No regen or DB possible • Large parts count • Reduced efficiency (many series IGBTs and diodes) • Special transformer required • Larger footprint in high HP	0.5 - 5 MW

Voltage Source Med Voltage PWM IGBT Inverter

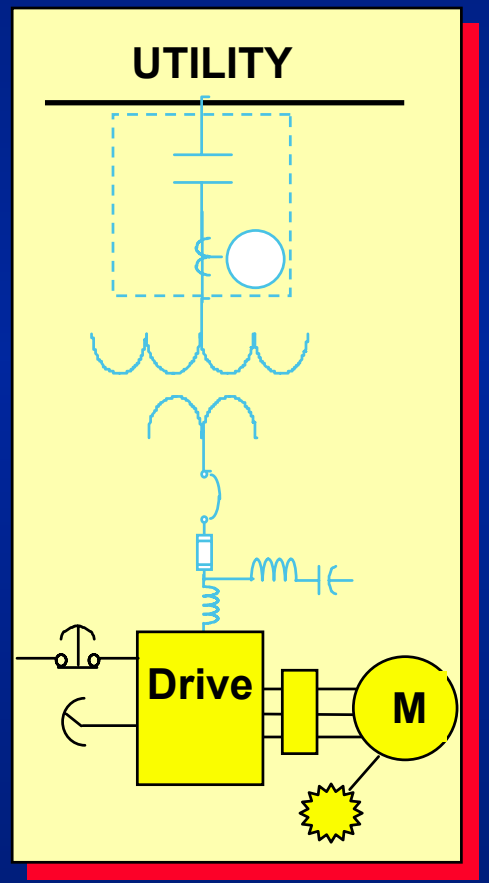


Inverter Bridge Topology Comparison

Inverter Topology	Advantages	Drawbacks	Practical Power Range
Three or Five Level Voltage Source IGBT PWM Inverter	• **Minimum parts count for voltage rating** • **Full regen and DB available** • **High efficiency** • **Low motor current THD** • **Low motor insulation stress** • **Easy repair** • **Fast transient response** • **Wide motor frequency range** • **Smooth low speed operation**	• **Motor termination impedance matching [3 level only]** • **Not N+1 redundant**	**0.5 - 5 MW**
GE Innovation Three or Five Level Voltage Source IGBT PWM Inverter	• Inverter duty motor not necessary due to 3 or 5 level switching • Laminated bus which has lower parasitic inductance that allows for a snubberless design • Fault current tolerance no longer an issue due to the use of IGBT's and optimized gate control. No inductor needed (di/dt limit) and no fuses (current magnitude protection) •Smaller footprint due to the use of heat pipe technology that improves power density		

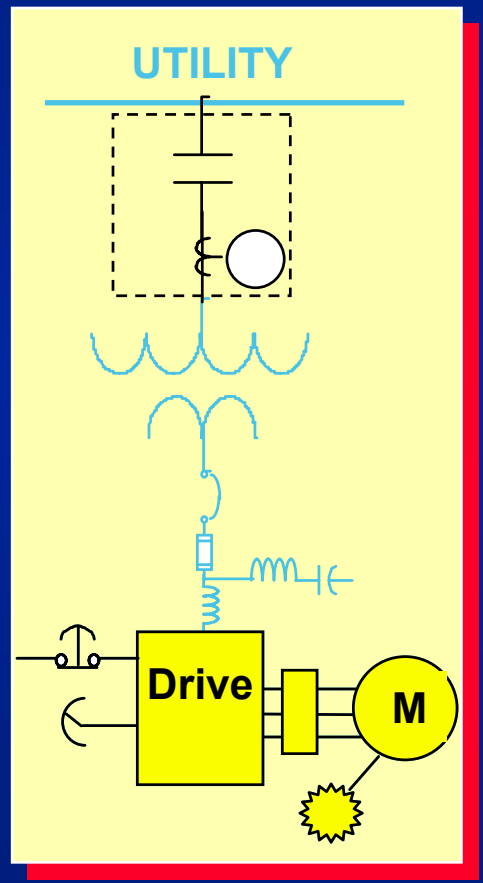
Utility Considerations

- Stiffness of supply
- Utility power level variations
- "Quality" of power as received
- Restrictions on power quality effects by new installation [power factor, harmonics]
- Impact of new loads on existing system.



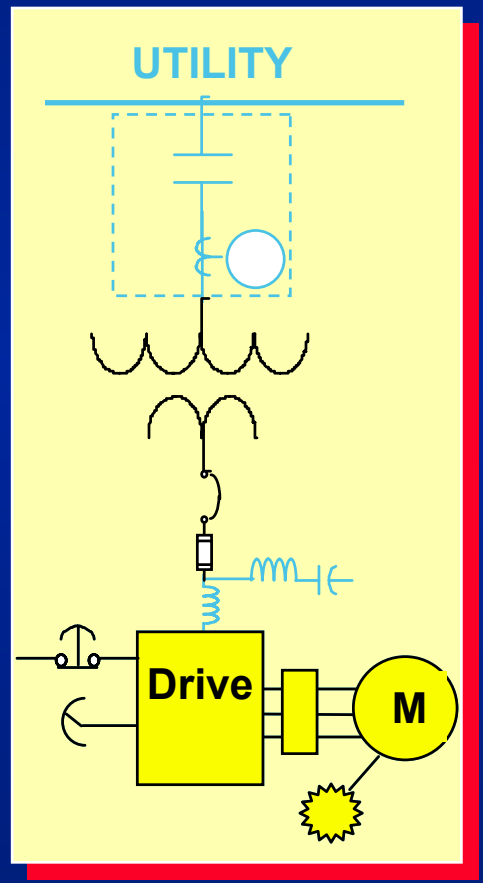
Power Control and Protection

- Medium Voltage switchgear
- Unique needs of drive-dominated loads.
- Metering, monitoring, and power management.



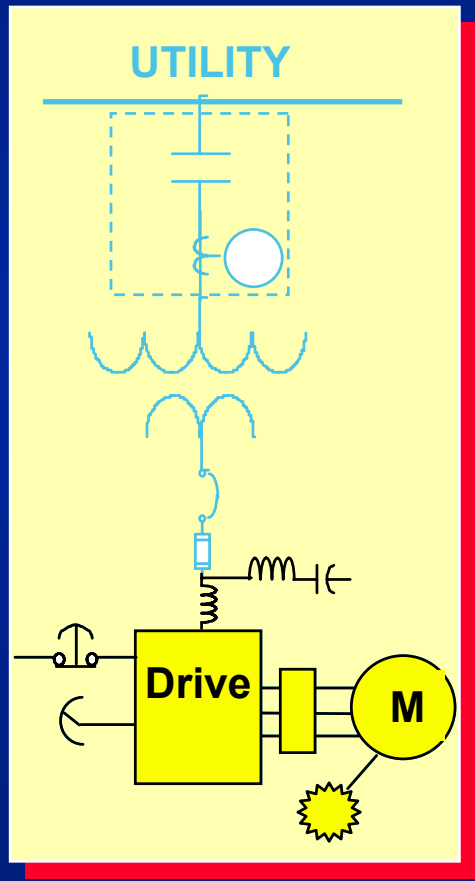
Power Distribution

- Harmonic effects on equipment
- True meaning of power factor
- Feeder sizing
- Mixture of drive and non drive loading.
- Transformer rating factors



Power Quality Issues

- Power disturbances on existing system.
- Injection of harmonics -
  - The problem & true impact
  - Specs, recommendations & regulations [IEEE-519 & others]
  - Rational solutions
- Economic tradeoffs.



IEEE 519-1992 Table 10.3 I_{TDD} Limits

Maximum Harmonic Curent Distortion in % of I-Load

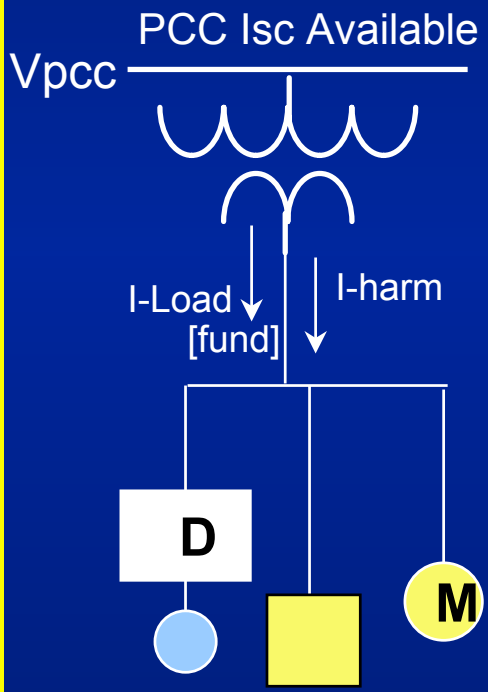
Isc to I-load Ratio	h < 11	h = 11 to <17	h = 17 to <23	h = 23 to <35	h = 35 & up	TDD %
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Notes: Even Harmonics limited to 25% of the harmonic level

TDD = Total Demand Disortion %, based on maximum demand current at the point of common coupling [PCC].

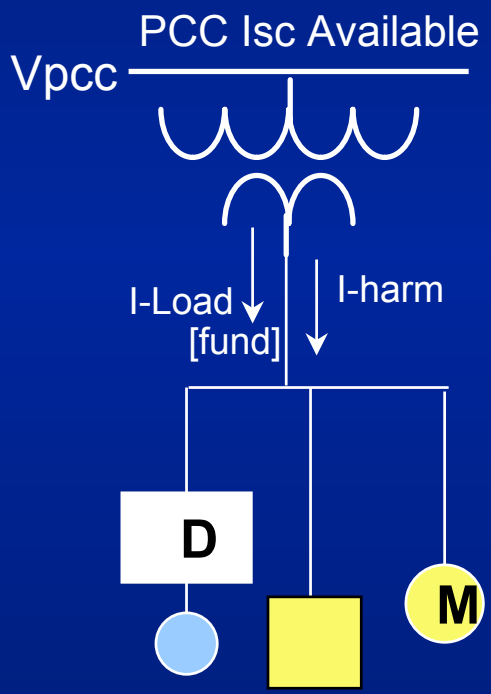
Isc = Maximum Short Circuit current or kVA at the PCC

I-load = Fundamental freqency load current or kVA at the PCC

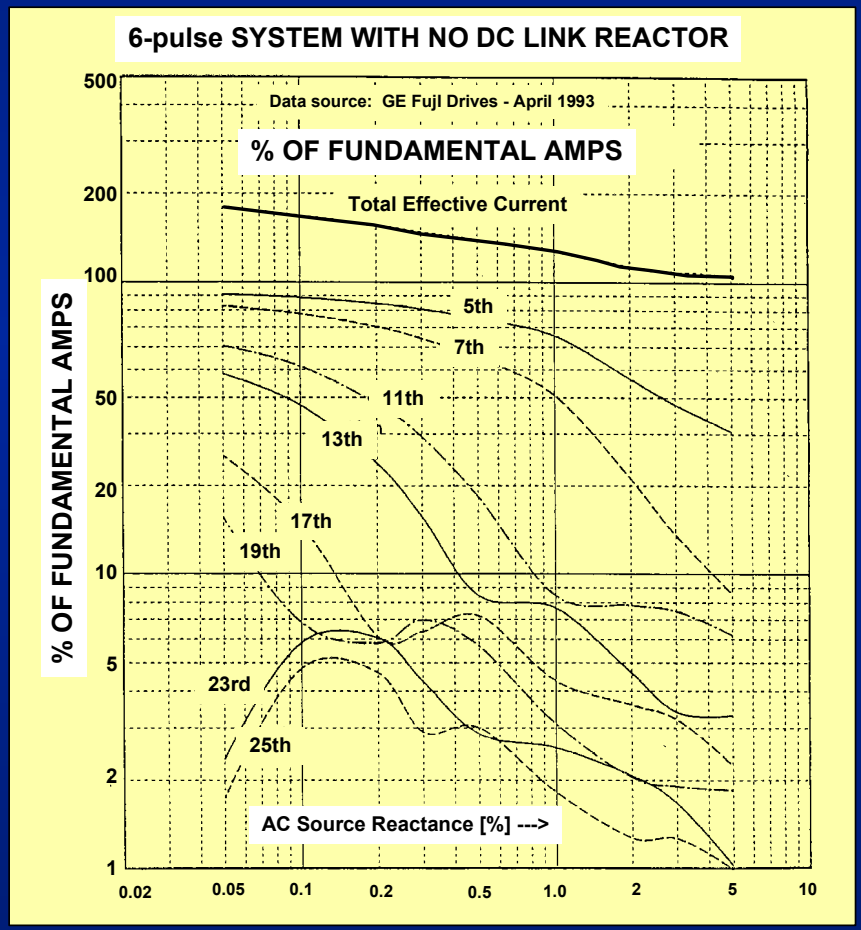


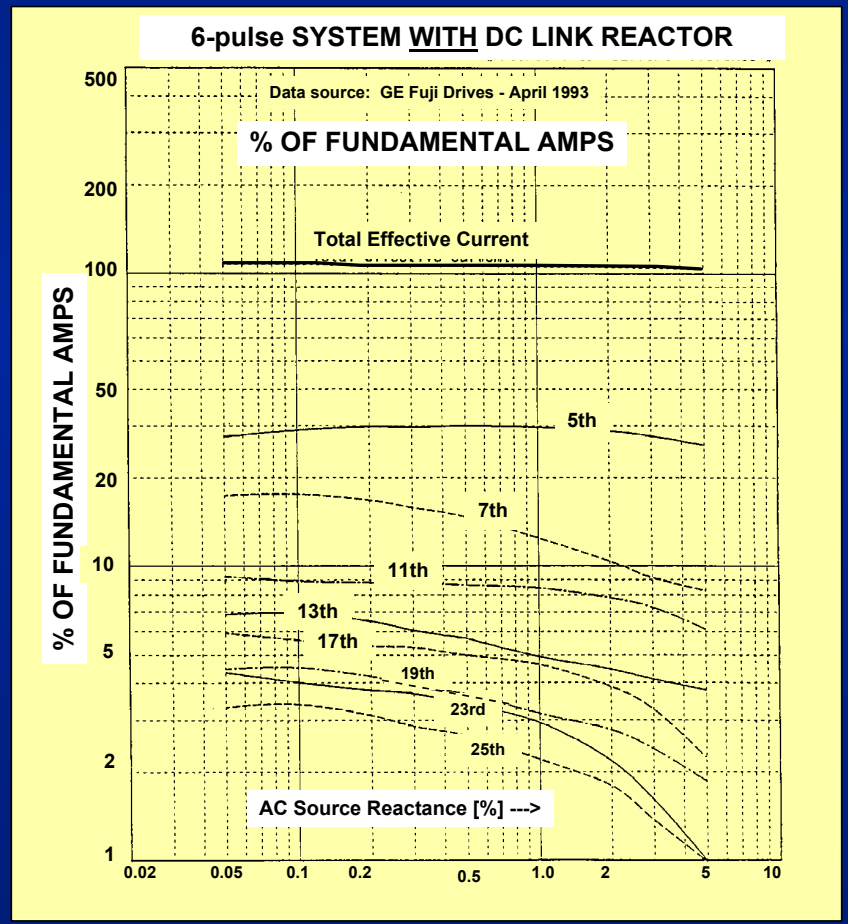
IEEE 519-1992 Table 11.2 V_{THD} Limits

- Voltage Distortion Limits for Individual Harmonic Number:
  < 3.0%
- Total Harmonic Voltage Distortion [V_{THD}] Limits for all harmonics:
  < 5.0%
- Voltage distortion is what is passed on to other equipment & utility.
- Voltage distortion depends on both injected current and source Z.
- THD within user system is separate concern, but not utility concern.



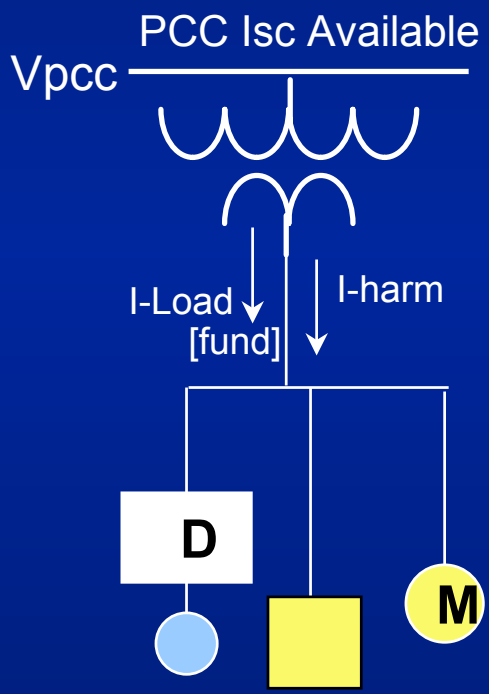
Typical Inverter Line Side % Current Harmonics



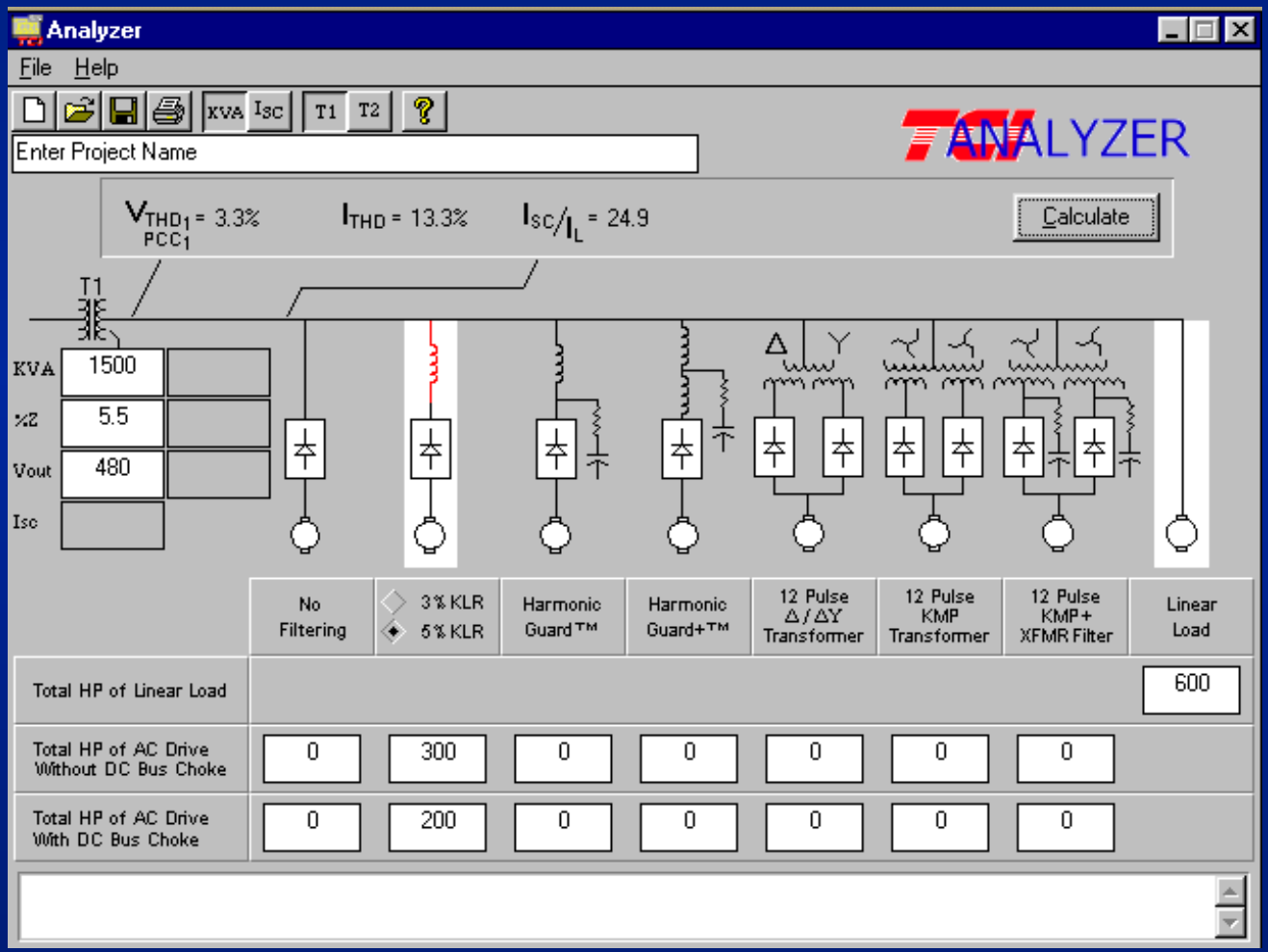


Harmonic Calculations

- Consider both drives and linear loads.
  - TDD per IEEE is a % of total kva, including non-VFD motors
- Demand distortion is not instantaneous number, but based on meter kva-hours.
- Must define a Point of Common Coupling: where currents sum.
- Computer programs are available [see www.transcoil.com].
- If you ignore harmonics, then breakers, transformers and feeders may be under-sized.



Simplified AC PWM Harmonic Analysis



TCI-Analyzer

- PWM VFD's with diode front ends
- Simple First-cut calculations.
- Allows rapid comparisons of drive & filter combinations
- Program available for purchase & download at www.transcoil.com

MV Filter- Metal Enclosed

- Air core or iron core inductors
- Oil filled capacitors
- L-C pairs Tuned to harmonics to be absorbed
- Switchgear and protection needed.

Stack-Rack Filter Banks

Open Construction

- Air core core inductors
- Oil filled capacitors
- L-C pairs Tuned to harmonics to be absorbed
- Switchgear and protection needed.

9 MVAR Bank, 12.47 KV, Tuned to 5th harmonic [5/98]

Typical Costs for MV Harmonic Banks

- Fixed = $30 / KVAR, Auto = $35-60 / KVAR
- Not including:
  - Taps for iron core reactors (typically 35% adder to cost & size)
  - Breakers
  - Disconnect switches, fused or unfused
  - Vacuum switches
  - Thermal protection for reactors (CT's & relays)
  - Unbalance/Blown Fuse detection (CT's & relays)
  - Automatic banks (controllers, switches & reactors for each step)
  - Ground switches
  - Ventilation/heaters
  - Provisions for Kirk key interlocks

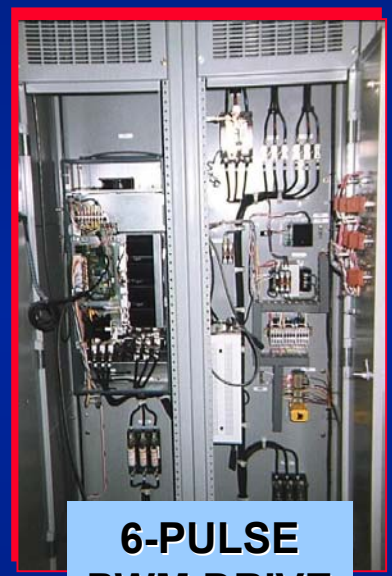
Typical Costs for LV Harmonic Banks

- Fixed = $70 to $180 / KVAR, Auto = $85 to $150 / KVAR, 480 volt or 600 volt
- Including:
  - Iron core reactors for each step
  - Contactors for each step
  - Breakers
  - Thermal protection for reactors (CT's & relays)
  - Unbalance/Blown Fuse detection (CT's & relays)
  - Ventilation/heaters

Low Voltage Harmonic Filters

For VFD Application

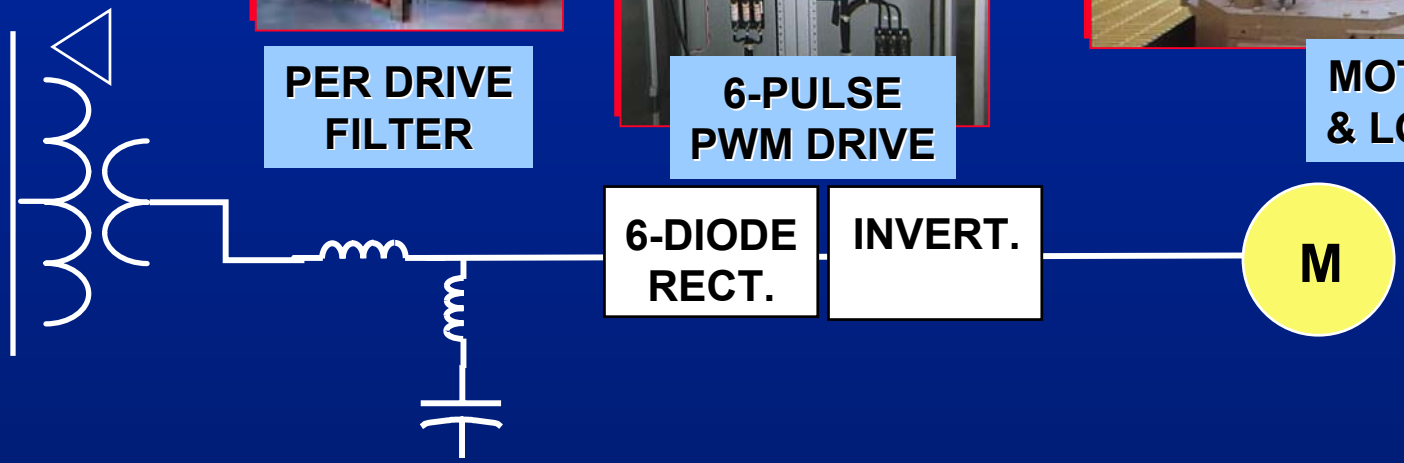
PER DRIVE FILTER



6-PULSE PWM DRIVE

MOTOR & LOAD

Incoming MV Feed

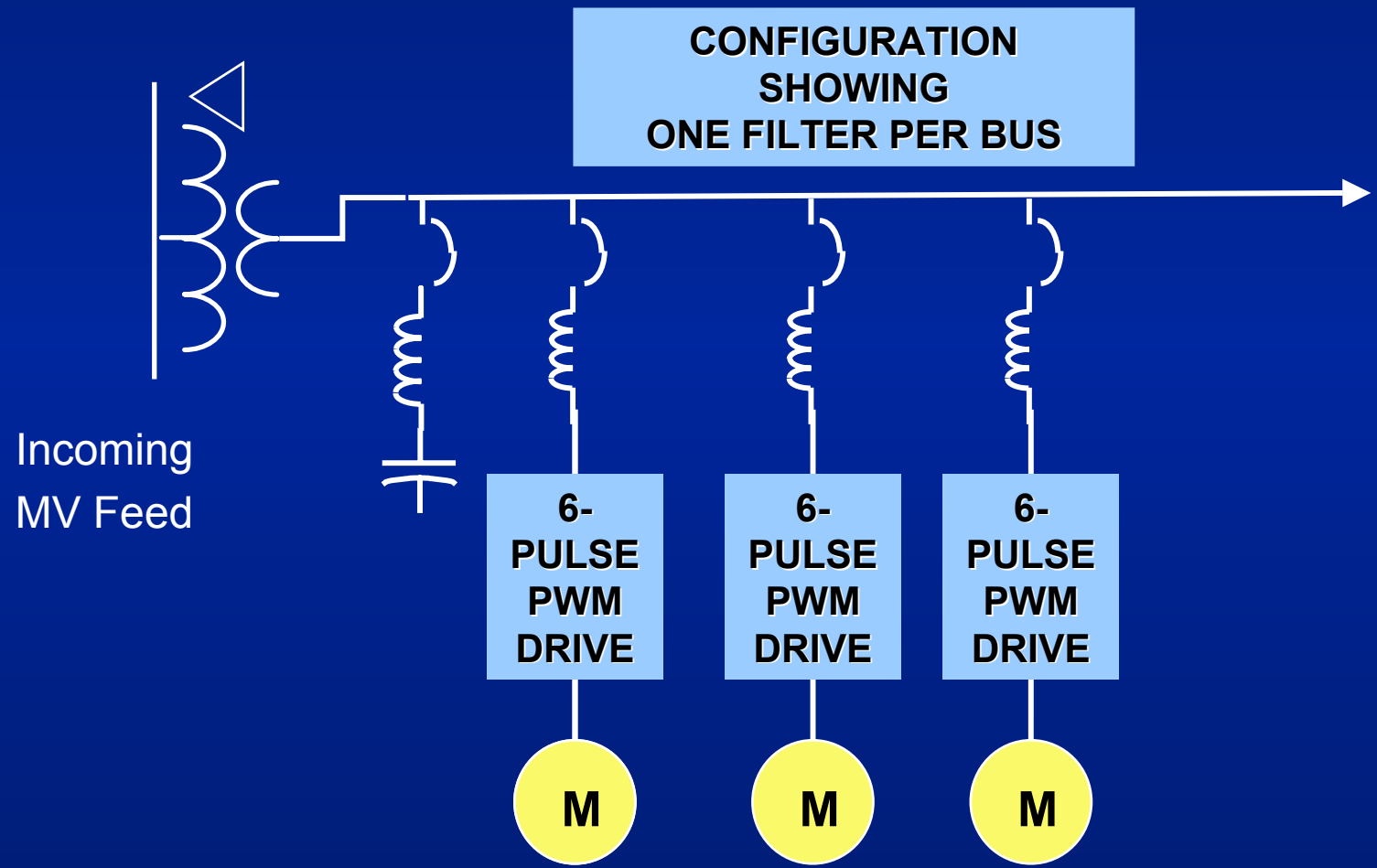


Harmonic Correction:
Rational Approaches

- Correct known problems, use consultation if needed.
- Local filters - at the source.
- System level filters.
- Minimize injection of currents by equipment selection & application.
- Maintain standards to prevent future problems.

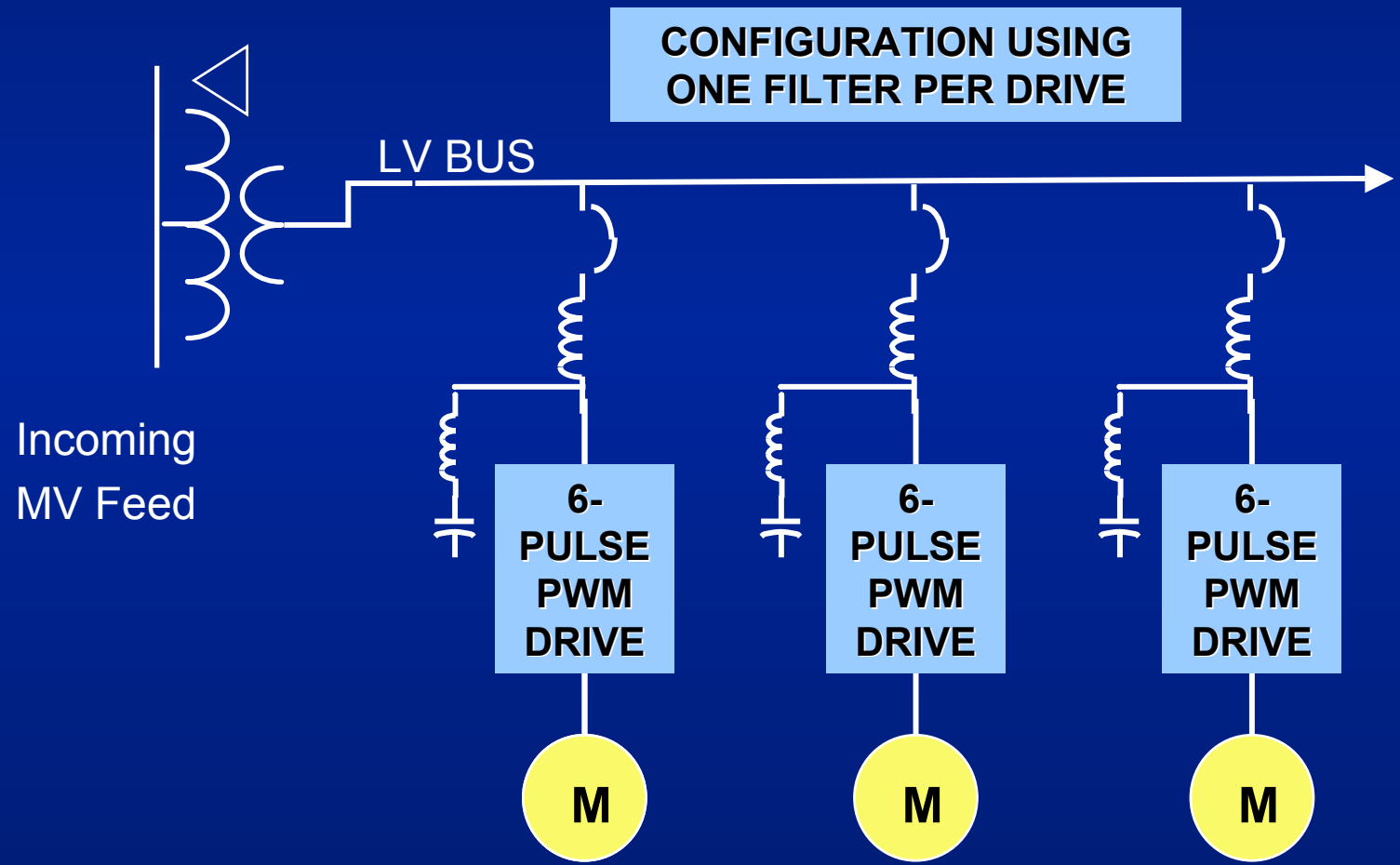
Low Voltage Harmonic Filters

For VFD Application

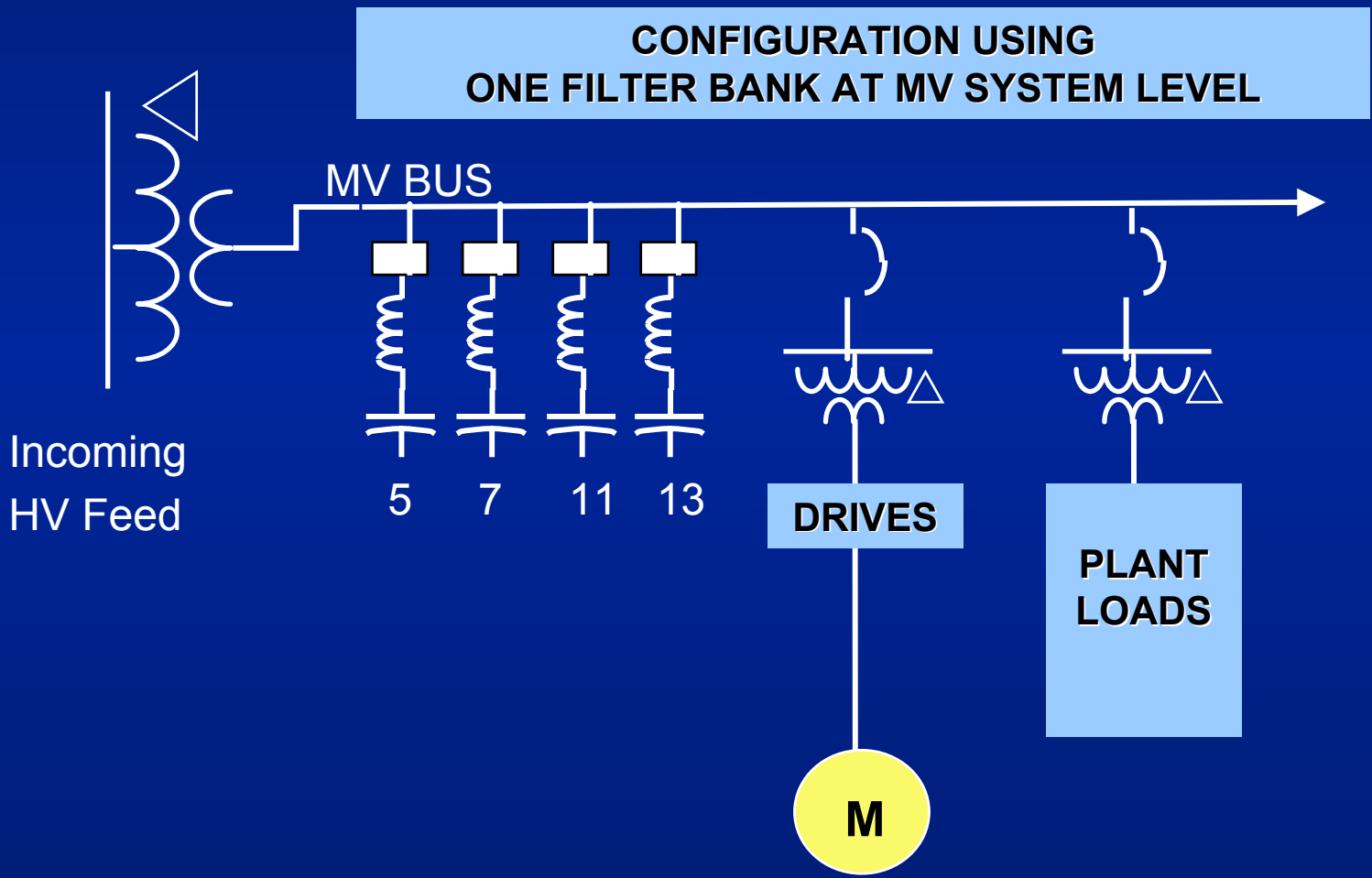


Low Voltage Harmonic Filters

For VFD Application



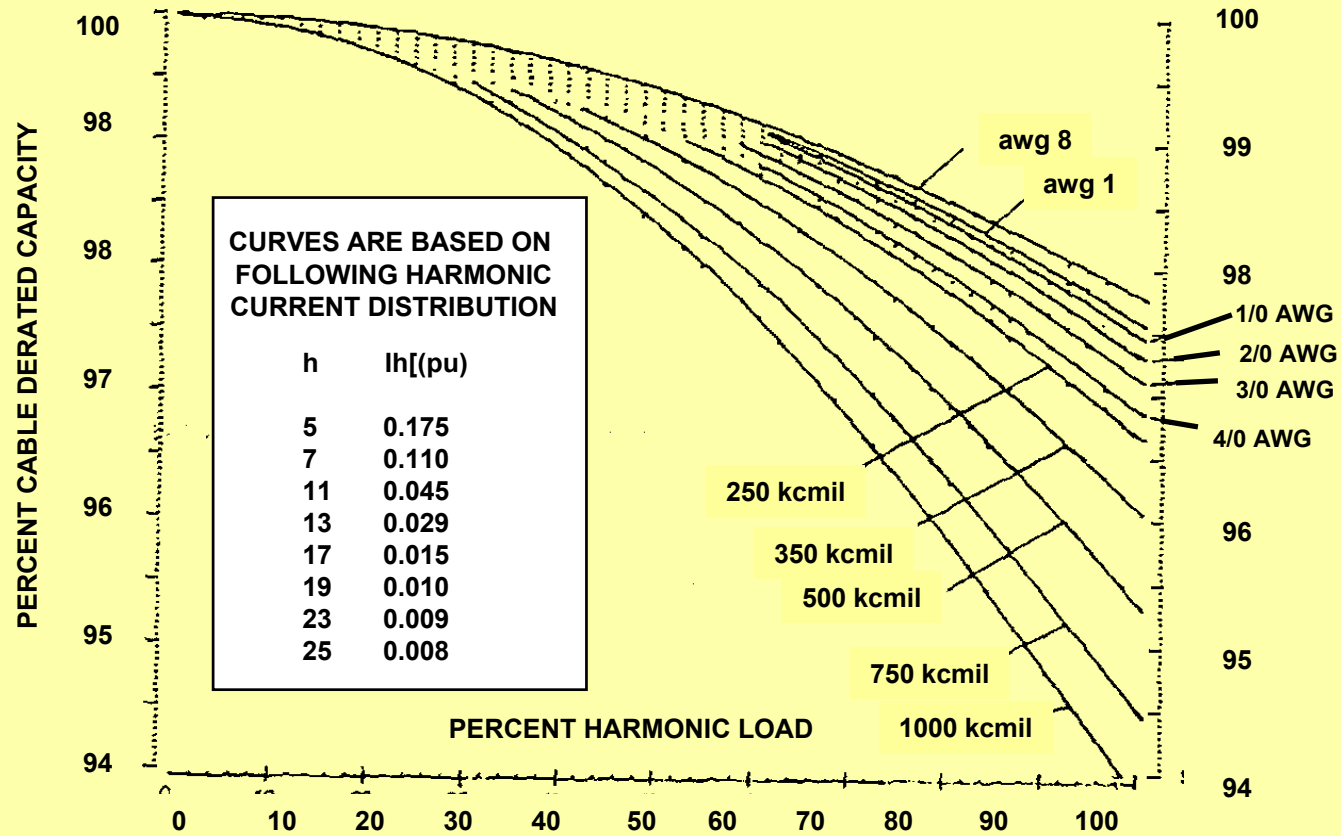
High/Med. Voltage Harmonic Filters



Power System Compatibility- Feeder Equipment

- Breakers, transformers, and cable must be rated to carry full kVA.
- Transformers need to be “drive isolation” rated with proper “K” factor.
  - ❖K 13 = 50% NL loads, K30 = 100%
- Equipment size may be minimized by reducing harmonics by using:
  - ❖Line & Link Reactors
  - ❖Filters
  - ❖Multipulse rectifier drives

IEEE 519-1992
Cable Derating Table



SIMPLIFIED CONCLUSION: REDUCE VFD HARMONICS TO THESE LEVELS OR LESS AND CABLE IMPACT WILL BE MINIMAL.

Harmonic Solutions

- Understanding
- Planning
- Studies & surveys
- Filters
- Low impact equip

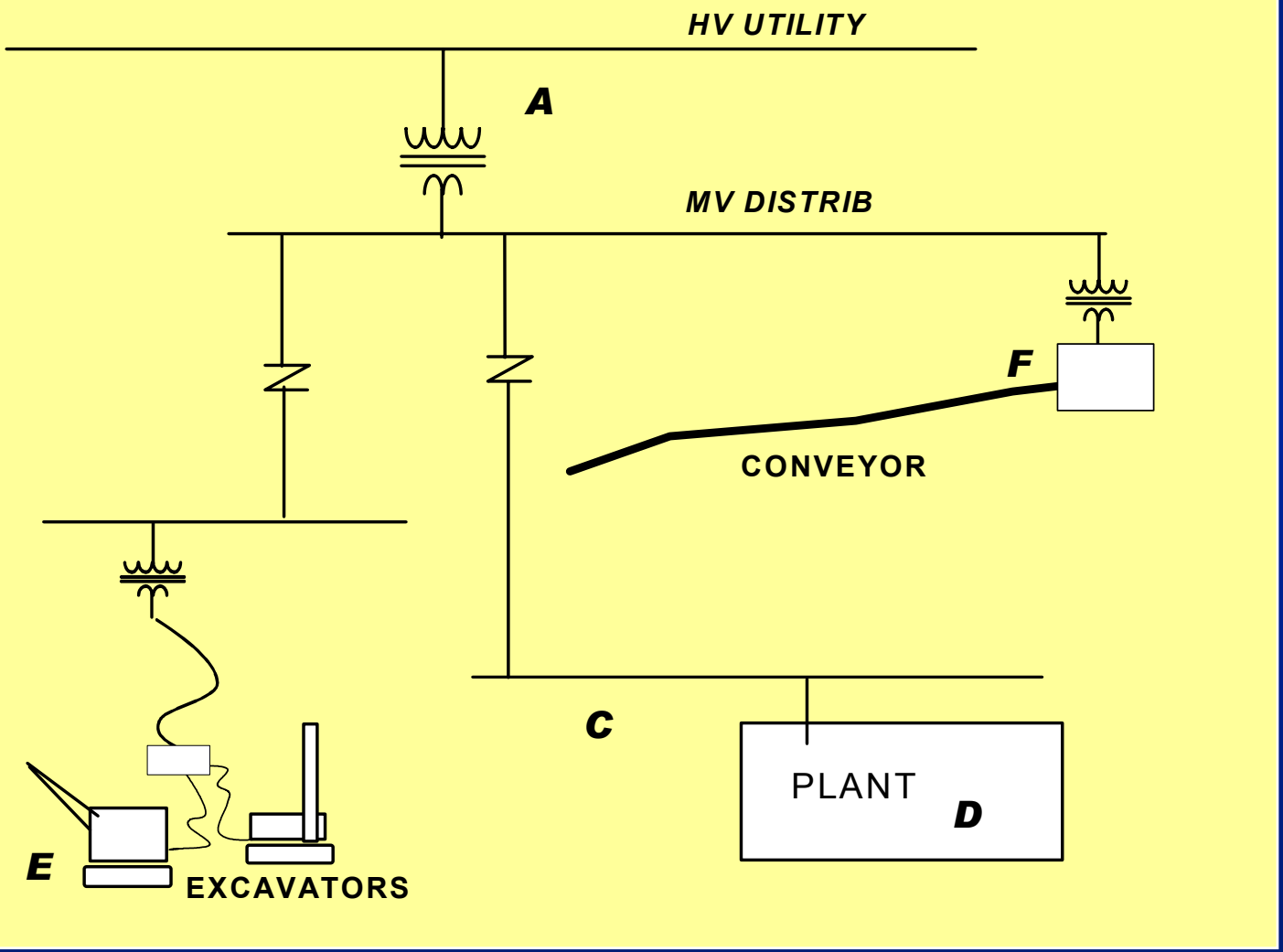
Harmonic Surveys

- What are they?
- When are they needed?
  - ❖Serious & widespread symptoms
  - ❖Starting fresh
  - ❖To fix utility complaints
- Localized or system wide?

Harmonic Surveys

- Do-it-yourself Approach
  - ❖Measurement locations
  - ❖Instrument availability, setup, calibration.
  - ❖Data interpretation
- When do you need professional help?

Example Power System



Using Harmonic Survey Results

- Recognize what data means trouble, and what can be ignored.
- Know the industry standards.
- Know how to apply standards with practical results in sight at lowest cost.

Summary

- Use common sense approach - don't be pushed into excessive action.
- Recognize symptoms of harmonic problems.
- Use design tools to do simple calcs and planning
- Consult reliable systems analysis sources when help is needed.

Summary

- Use common sense approach - don't be pushed into excessive action.
- Recognize symptoms of harmonic problems.
- Use design tools to do simple calcs and planning
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